Machining set-up planning based on evaluation of feature relations and fixturing constraints
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Abstract

A key activity in developing a process plan for machined parts is the planning of machining set-ups. This paper deals with the automatic generation of multiple machining set-ups given a feature-based part description. A hybrid object-oriented and rule-based approach is proposed to represent the declarative and procedural planning knowledge. Declarative knowledge is employed to identify machining feature groups. Procedural knowledge regarding machine tool capability, feature precedence and fixture interaction is used to generate machining set-ups. The paper presents a set-up planning system based on the proposed approach. The system is for prismatic parts produced on a three-axis vertical machining centre.

1. Introduction

Computer Aided Process Planning (CAPP) is the link between design and manufacture. Effective CAPP is useful to a concurrent engineering system. An important activity of CAPP in a machining context is to determine the set-up scheme for each operation. A set-up groups machining sequences that are all made in one particular orientation of a workpiece. Set-up planning requires expert knowledge.

In the last two decades, many CAPP systems have been developed (Alting & Zhang [1] and Maropoulos [2]). Several CAPP programs using expert system shells and 3D solid modelling software have been developed. Some researchers have paid more attention to fixture planning (Pham et al.[3], Ngoi et al. [4] and Roy & Sun [5]), while others have separately studied machining and set-up planning (Abdalla & Knight [6], Case et al. [7] and Opas et al. [8]). However, a good process plan cannot be devised without taking into
account set-up and fixturing requirements simultaneously. The question of how to grip the workpiece while it is being machined and how to machine features in a set-up must be considered at the same time to arrive at an optimal process plan.

Set-up planning studies have produced solutions for individual set-ups to machine features on one side of a part. However, examining only individual set-up requirements is not sufficient to generate a set-up plan. The machining of many parts requires multiple set-ups. Therefore, multiple set-up requirements should be considered. For this purpose, Chang [9] has used feature clustering based on the tool approach direction. Set-ups can be determined by refining the clusters. Hayes and Wright [10] have used feature interactions in constraining operations for multiple set-up planning for a vice. Kambhampati et al. [11] and Lee et al. [12] have focused on geometric reasoning for fixture and multiple set-up planning. Ferreira and Liu [13] have developed a rule-based system for automatically generating workpiece orientations, each orientation corresponding to a set-up. Gu and Zhang [14] have used the number of features to be machined to choose a set-up sequence for a vice.

The fixture configuration adopted affects set-up planning as it must allow the required tool path in the specified set-ups. Geometric tolerances and feature precedence relations of the workpiece also play an important role when the set-ups are decided.

This paper describes the automatic generation of set-ups for prismatic parts on a 3-axis vertical machining centre. A hybrid expert system for multiple set-ups planning is presented. The system takes into account fixturing constraints as well as other constraints related to the workpiece and machining operations.

2. Proposed System

Because set-up planning is a knowledge intensive activity, a knowledge-based approach is appropriate. To implement the proposed system, the KAPPA-PC [15] knowledge-based shell was selected. This uses a hybrid representation approach which supports object-oriented programming and rule-based reasoning. Figure 1 shows the overall structure of the system.
Information on the part, such as features, faces, dimensions, datums and geometric tolerances, is stored in the knowledge base as objects, attributes and values. This information is automatically extracted from a feature-based 3-D solid modelling CAD system [16] that implements both the Boundary Representation and Constructive Solid Geometry methods. As shown in Figure 2, the part and its details are represented as a hierarchy of classes, subclasses and instances. Every branch in the hierarchy contains attributes as slots. In addition to this encoded declarative knowledge, the system also has knowledge which allows it to work intelligently in the given problem domain. One of the commonly used knowledge structures is production rules which are for manipulating the declarative knowledge. This procedural knowledge is stored in the knowledge base and describes how the problem is solved. An example rule written in KAL, the procedural language of KAPPA, is shown in Figure 3. The reasoning strategy of the inference mechanism is chosen according to the problem type. For this set-up generation problem, which is a data-driven problem, a forward-chaining reasoning strategy was selected.

The proposed system operates as follows. Feature groups are created for a given part based on feature approach directions and pruned using the procedural knowledge. Relationships among the features are then identified. This process reveals which features can be machined in the same set-ups. Finally, the machining set-ups and overall fixture configurations are identified.
3. Approach Direction

Features must be orientated correctly with regard to the spindle axis of the machine tool. As mentioned above, to determine features that can be machined in the same set-up, the features are grouped according to their tool approach directions. The tool approach direction is an unobstructed path along which the tool can approach the feature. All approach directions of the features to be machined have to be determined.

In the current study, the features considered are steps, through slots, open slots, corner notches, pockets, blind holes and through holes. These features may be approached along one or more orthogonal directions ( +X, +Y, +Z, -X, -Y, -Z ). There may be features with approach directions that are different from those six orthogonal directions. Such features have more expensive process and fixturing requirements. An aim is to avoid awkward approach directions. The
evaluation of feature surfaces in terms of available tool approach directions has
been described by Göloglu [17].

4. Feature Clustering

Features with the same tool approach orientation can be machined in one set-
up. These features form the feature clusters.

Some features may be placed only in one cluster, while others may
belong to more than one cluster. When a feature belongs to more than one
cluster, refinement of the clusters is required. In this pruning process, the
objective is to reduce the number of set-ups. The result of the pruning process
is the final feature clusters. Forward chaining is employed to perform pruning.
Some of the pruning rules used are:

- Leave the through hole in the cluster with the maximum number of features.
- Eliminate the approach direction that is different from the six orthogonal
directions for a corner notch.
- Cluster a step according to the normal of its largest surface area.

5. Feature Precedence Relationships

Associated with a feature are relations which specify its size and geometry. The
main relations are dimensional relations, parent-child relations and geometric
tolerance relations. These can affect the sequence in which the features are to
be machined and thus have to be taken into account in planning set-ups.
Relations are identified by declarative knowledge in the knowledge base.
Dimensional relations express the size of a feature and reference connections.
A feature can be nested within a parent feature or within the main feature via its
reference surfaces or edges. If a feature is nested within another feature, the
nested feature becomes a child of the reference feature. This kind of relation is
called a parent-child relation. Geometric tolerances, or form and orientation
tolerances, are used to indicate the importance of the function of a feature.
They show the admissible deviations on nominal geometric relations. Form
tolerances do not require any datum references while orientation tolerances
need one or more datum references. Orientation tolerances are those concerning
parallelism, position, angularity, perpendicularity and concentricity. Figure 4
illustrates the dimensional, parent-child and geometric tolerance relations in an
example part.

If the process of identifying relations reveals unmachined surfaces that
are used as references, they are included in the appropriate feature clusters.
6. Datum Selection and Fixturing Configuration

Some surfaces of a workpiece are used as datum elements to machine the rest of the surfaces or features. A datum can be described as a plane which serves as a reference between features and surfaces. During machining, the part can be securely held in a required location by using set-up datums. Proper holding increases the productivity as well as the accuracy of machining. As mentioned previously, when dealing with prismatic part, some authors have assumed that a vice is used. The proposed system does not rely on vices but allows parts to be properly fixtured as explained below.

A prismatic part has three degrees of linear freedom (±X, ±Y, ±Z) and three degrees of rotational freedom (±α, ±β, ±θ). The most common method of restricting the freedom of a part is the 3-2-1 location principle (Menassa [18]) (see Figure 5).

The largest flat horizontal surface of the part is used as a supporting datum surface. Three support elements below the part provide a stable primary location. They define the primary datum plane and establish a vertical stop against the gravitational loads and machining forces along the Y axis. Three locator elements are placed on two perpendicular vertical faces. They effect the location of the part on the secondary and tertiary datum surfaces along the X and Z axes respectively. The second largest face after the primary datum surface is selected as the secondary datum with two locators on it. A clamp is employed to lock the workpiece onto the support and locator elements. The
position of the clamp should be chosen such that cutting tools cannot interfere with it. Clamp elements can be positioned on vertical or horizontal surfaces of the workpiece.

Figure 5. The 3-2-1 fixturing principle

The selection of supporting, locating and clamping contact planes is done by identifying the datum planes. A datum plane should allow inspection and measurement of the machining features in a given set-up. In this study, proper selection of datums and interaction between tool and fixture configuration were the main criteria in determining machining set-ups. The following algorithm was used to identify the datum planes:

• Find the largest feature cluster that has not yet been considered.
• Based on the identified feature precedence relations, check whether the features of the cluster have any specified geometric tolerances or external unmachined reference surfaces. If there is a feature with geometric tolerances relative to unmachined surfaces or if there exist unmachined external reference surfaces, then take the largest of those surfaces into consideration first.
• Select the surface opposite to the surface under consideration as the primary datum plane to position the part on it.
• Find all external outer surfaces that are perpendicular to the primary datum plane.
Select an already machined surface from the above group of surfaces as the secondary datum plane. If no machined surfaces are available, use the largest unmachined surface.

Find all the surfaces perpendicular to both the primary and secondary datum planes.

Give priority to machined surfaces in choosing the tertiary datum plane.

Find surfaces and features that are not referenced to unmachined features and assign them for machining in the same set-up. Surfaces and features that are referenced to unmachined features can also be assigned to the same set-up if the unmachined reference features can be machined in that set-up.

For clamping surfaces, use external surfaces that have not been specified as datums and that are not surfaces in which the features being machined are nested. This is to avoid interference between the clamping elements and the tool. Normally, the largest surfaces opposite to the datum surfaces are candidates for clamping.

Repeat the above procedure until all features to be machined have been assigned to set-ups.

7. Case Study

The part for which a set-up plan will be identified is shown in Figure 4. All the design requirements are specified for the part during the design phase in the CAD environment. Information related to design features is automatically extracted from the CAD system and stored into the knowledge base. This information is used for determining the feature access directions and identifying the feature relations.

The given part has thirteen features: three blind holes, three through holes, two through slots, an open slot, a step, a pocket and two corner notches. Their approach directions are automatically identified as shown in Figure 6a by manipulating information in the knowledge base. The existence of feature dimensional relations may increase the number of machining features because such relations involve reference surfaces. The reference surfaces must be machined before the related features. In the current part, Face_20 and Face_2 are reference surfaces, because they are used for positioning feature Feat_388 and for its geometric tolerance specifications. Face_11 is used for referencing Feat_36, Feat_69, Feat_89, Feat_141, and Feat_503. Because of their status as reference surfaces and because they are unmachined, Face_20, Face_2 and Face_11 are included in the appropriate clusters of features to be machined. Figure 6b shows the complete dimensional, geometric tolerance and parent-child relationships between features and surfaces.

After all machining groups and feature relationships have been determined, the next goal is to identify the set-up plan. The system starts by finding a suitable supporting surface as a primary datum plane. For this purpose, as explained earlier, the system searches the direction in which the
Figure 6. a) Feature clusters, b) feature relationships c) set-up plan for the example part
maximum number of features is nested. In the example part, the most frequent feature carrier direction is the positive Y direction. The surface opposite to this direction (Face_22) is adopted as the primary datum plane. The location surfaces, Face_2 and Face_24, are selected by finding surfaces perpendicular to the primary datum. The clamping surface (Face_30) is chosen from those surfaces opposite to the datum planes. After the fixturing configuration has been determined, Face_11, Face_20, Feat_36, Feat_69, Feat_89, Feat_141, Feat_109 and Feat_178 are assigned to the set-up. However, some features remain unassigned. Examples are Feat_258 and Feat_388 which have relations with Face_2 (see Figure 6b), an unmachined surface serving as a datum and therefore not machinable in the current set-up. The forward chaining inference mechanism is terminated when all the machining set-ups are identified. The process gives all machining set-ups required to machine the part. The set-up plan of the sample part and user interface windows are shown in Figure 6c and Figure 7 respectively. Note that the operations listed for each set-up are not in any particular order, the sequencing of operations being carried out by applying sequencing heuristics after the set-up plan has been derived.
8. Conclusion

Set-up planning has so far been given little attention. The extensive heuristic knowledge required has forced set-up planning activities to be done manually. As demonstrated by the work described in this paper, the availability of knowledge-based systems provides opportunities for this area.

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