Feature-based machining precedence reasoning for prismatic parts in CNC process planning
Gui, Zhonghua; Yeung, Millan K.

Publisher's version / Version de l'éditeur:

Proceedings of the 14th International Conference on Flexible Automation and Intelligent Manufacturing, 2004-07-12

Feature-based Machining Precedence Reasoning for Prismatic Parts in CNC Process Planning

Zhonghua Gui[1] and Millan K. Yeung

Integrated Manufacturing Technologies Institute
National Research Council Canada
800 Collip Circle, London, ON, N6G 4X8, Canada

Abstract

Precedence relations are crucial to operation sequence planning, and must be satisfied in determining an operation sequence. Most of the previous research work has focused on how to optimize operation sequence and assume that the precedence relations are given as input, or specified interactively by the users. However, to obtain precedence relations, especially to automatically generate precedence relations using knowledge of feature interactions imposes an interesting challenge for Computer Aided Process Planning? (CAPP). This paper presents a definition for feature accessibility and a method to obtain its geometric precedence relations using the updated feature iMaginary face-Real face (M-R face) dependency and the accessibility of the cutting tool to the feature. This method allows the dynamic generation of geometric precedence relations based on the setup direction, updated topologies and interactions between the features. The geometric precedence relations could be influenced by the reference precedence from tolerance specifications and the machining expertise precedence relation input from machining experts. The precedence-reasoning module is currently being implemented within a CNC computer-aided process planning system for prismatic parts.

1. Introduction

The optimization of operation sequences has received significant attention within the research community. For a given part, the machining operations cannot be performed in an arbitrary order. In general, geometric and machining specific constraints will determine the precedence of certain operations over the others. A number of systems have been developed to optimize operation sequence upon the precedence constraints predefined by users. However, only a few research publications emphasized on how to generate precedence relations based on the knowledge of interactions between features.

In [4], an Attributed Adjacency Graph was used to recognize concave features and a heuristic opens-into relation was defined to capture precedence information between recognized features, but it did not properly classify all cases of interacting features. In [3], feature classes were defined according to the shape and trajectory of milling and drilling tools, and discussed the accessibility precedence constraints between features and the datum surface dependency constraints from the tolerance specification. Accessibility precedence constraints of a feature were obtained by testing for interference between the approaching tool and all other feature volumes, which could be very expensive on computation. In [7], Heuristic techniques were used to determine precedence constraints between features. A number of rules based on machining practices have been defined and were used to determine precedence constraints between pairs of features. The features in this approach were allowed to have multiple approaching directions and might require conditional precedence constraints. In [5], the precedence relations were generated between features using the face dependency obtained by ASVP Decomposition (Alternating Sum of Volumes with Partitioning). The ASVP was also applied to obtain the Form Feature Decomposition (FFD) of the part model. The face dependency and precedence tree proposed in the paper ensured the exposition of open faces or entrance faces of the feature and hence its accessibility. However, the Tool Access Direction (TAD) constraint was not discussed.

In this paper, iMaginary to Real (M-R) face dependency is proposed to represent feature interactions for the automatic generation of feature geometric precedence relations. The definition of feature accessibility and the method to generate the geometric precedence based on M-R face dependency and tool accessibility constraints are

1 Zhonghua Gui: Tel.: (519) 430-7075; Fax: (519) 430-7064; E-mail: zhonghua.gui@nrc-cnrc.gc.ca

presented. Future enhancement will include the manipulation of tolerance specifications and inputs from machining experts.

The method proposed aligns with the functionality of the "Feature Extraction" module of an Intelligent Process Planning System for CNC programming described in [11]. The paper is organized into six sections. Section 1 gives an introduction of the research work. Section 2 describes the definition of features and the information required for determining the feature interaction and generating precedence relations. Section 3 describes the feature-based model created by Volume Decomposition feature recognition method [6]. Section 4 presents a definition for feature accessibility that determines the geometric precedence based on M-R face dependency and tool accessibility constraints. Section 5 gives a case example of generating feature precedence relations for a prismatic part. Finally results and future works are discussed in Section 6.

2. Feature Definition

2.1 Feature Definition

Features are entities on which planning decisions can be based on. They are parametric and associated with attributes such as length, width, depth, position, orientation, geometric tolerances, material properties, and references to other features. Thus, features have a higher semantic level than the primitive elements used in ordinary CAD systems. The representation of feature must be able to capture both the complex geometry and its relationships with other features and cutting tools. The features in the context of this paper are restricted to machining features only, which can be considered as a portion of a part having some manufacturing significance and can be created by machining operations.

A machining feature is considered a volume to be removed by a series of machining operations. Case, K. [1] defined the geometric aspects of features as volumes enveloped by a set of real and imaginary faces. The real faces physically exist on the component and are typical surfaces on the original blank or the result of manufacturing operations. The iMaginary Faces (MF) can be considered as the surfaces required together with the real faces to form an enclosed volume. Such a definition allows individual features to be represented as distinctive solid objects and therefore they can be edited, manipulated and retrieved independently in solid modeling system.

The slot in Figure 1 is represented as a solid object with six faces. When this solid is "subtracted" from the component, three of the faces will appear as real faces on the component. The remaining faces will not appear and are therefore referred to as imaginary faces of the feature.

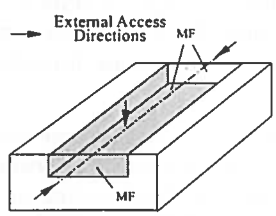


Figure 1. Through Slot Feature

All other features have a similar defined representation, with a fixed and characteristic number of imaginary faces and a profile shape dependent on the number of real faces.

2.2 Feature Taxonomy Scheme

Gindy's feature taxonomy (Figure 2) [2] provides the required rigid and complete structure for feature primitives. Features are characterized by the number of orthogonal directions, from which the feature volume might be accessed. These are known as External Access Directions (EADs), and all features will have between 0 and 6 EADs. The three external access directions for a through slot are shown in Figure 1. Further classification on the basis of the type of profile (open or closed) and whether or not the feature volume penetrates through the component gives the nine basic feature classes (bosses, pockets, holes, non-through slots, through slots, notches, steps, real surfaces and imaginary surfaces).

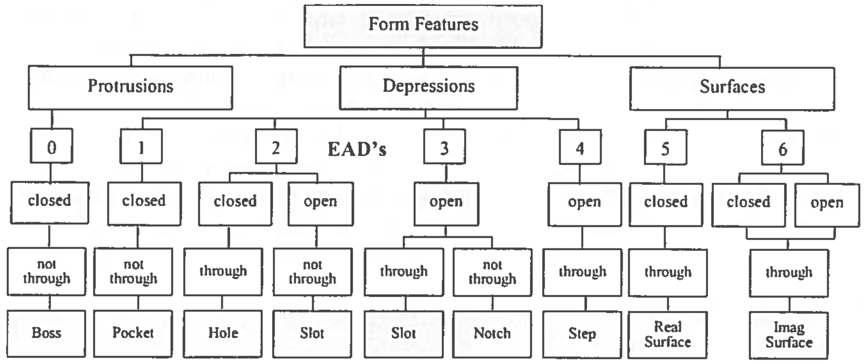


Figure 2. Feature Taxonomy

2.3 FEATURE PARAMETERIZATION

Features were characterized by position and orientation parameters, including an origin *O*, a depth direction *D*, and, if applicable, a width direction *W* in [5]. These parameters, together with a third direction given by $D \times W$, define a local coordinate system for each feature type. Additional dimensional parameters measure length, width, height, and radius. The depth direction *D* corresponds to the Tool Access Direction (TAD).

The topologies of feature definition for the through hole, pocket, through slot, blind slot, notch, and step feature are shown in Figure 3. For more topologies of feature definition, refers to [9]. The Tool Access Direction (TAD) is depicted in figures with a thick arrow next to the feature. Some features have multiple TADs and can be parameterized according to each TAD. The result is a set of different orientations of the feature's local coordinate system. It corresponds to different setups for the machining of the feature. For examples, the top-down or bottom-up TAD for a through hole, and the top-down or right-to-left TAD for a step as in Figure 3.

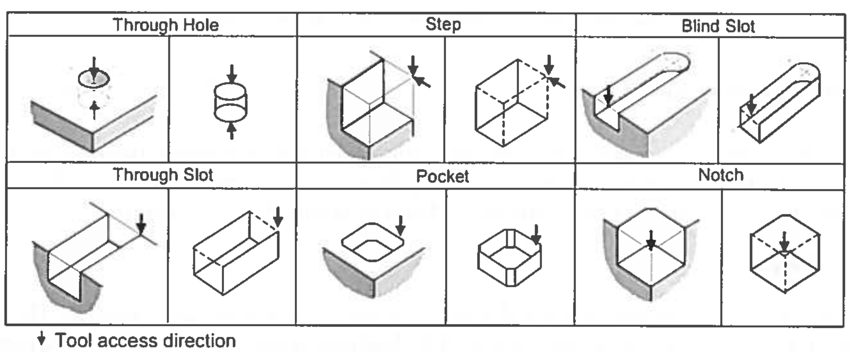


Figure 3. Features Topology and Their Tool Access Directions

3. FEATURE-BASED PART MODEL

To identify features, the concept of volume decomposition is used [6]. Following are some of the terminologies used in the model.

Raw Part Model (RPT) a 3D stock specified by a user

Final Part Model (FPT) a 3D part to be produced from a RPT

Total Removal Volume (TRV) the Boolean difference of the RPT and FPT. It may consist of one or more disconnected bodies or lumps

Machined face (M_face) the face on the FPT at which material is removed by machining processes from the RPT

To illustrate the concept, let F and R be solids representing the FPT and RPT respectively. The initial input to the system is the FPT, RPT and their relative positions in the workspace. The TRV is obtained by a Boolean decomposition process, i.e. TRV = R – F. The TRV is decomposed into a set of delta volumes and these volumes correspond to distinct machining features. The faces of each machining feature are primarily categorized into two types, the machined face (M_face) – real face of the feature, which is the M_face or extension of M_face of FPT, and the non-machined face (NM_face) – imaginary face of the feature, which is a portion of boundary surface of RPT or a theoretical boundary face of the feature for separating two adjacent features in decomposing TRV. The imaginary face is a significant parameter in the model for process planning. For example, the normal vectors of imaginary faces are the potential tool access directions and the imaginary faces may be used to determine safe clearances for the cutting operations [1]. The definition of a through slot in Figure 1 is a good example.

TRV can be decomposed into a set of feature volumes and is expressed as

$$TRV = \{\Delta V_1, \Delta V_2, \Delta V_3, \ldots, \Delta V_n\} \tag{1}$$

where n is the number of feature volumes, ΔV_i a single feature volume and i = 1, 2, …, n .

$$\Delta \overline{V_i} = \sum_{i=1}^{m} M\_face_i + \sum_{j=1}^{n} NM\_face_j \tag{2}$$

where $\Delta \overline{V_i}$ is the boundary of a single feature volume, m is the number of M_faces and n is the number of NM_faces of ΔV_i, and i = 1, 2, …, m and j = 1, 2, …, n.

The steps to generate the feature representation proposed in section 2 are fairly straightforward. Take the Boolean difference between the R and F to generate the TRV. Decompose the TRV into a set of sub-volumes ΔV_i and hence a set of distinct machining features. These machining features define the feature volume model.

Finally, for all the feature volumes generated, they must be verified and validated with the following.

Validity Verification: a valid feature must produce some portion of the M_faces of FPT.

Completeness Verification: all the features must produce all the M_faces of FPT.

Accessibility Verification: For every feature, its accessibility verification is obtained by testing for interference between the approaching tool and part such as ray-casting test.

4. Feature Precedence Relations

In order to obtain precedence relations automatically using feature recognition, the derived knowledge about the interaction between the features is important in sequencing them. A clear understanding and classification of feature relationships plays an important role in generating precedence relations between features.

4.1 Feature Accessibility

The generation of feature precedence relation described is based on feature accessibility. The features are divided into two categories of accessible features and inaccessible features according to their tool access direction, and the updated blank configuration. The imaginary faces of accessible features are boundary faces of the part. These accessible features are usually at the outer layer of the blank and have higher priorities to be machined first. On the other hand, some of the imaginary faces of inaccessible features are obstructed by other features of the part and therefore they can only be machined after the corresponding features containing these imaginary faces are produced.

The overall methodology is initially to classify the features into the corresponding accessible and inaccessible categories, process the accessible features, and then the inaccessible features. These steps are repeated until all the features have been processed. Therefore, the criteria for determining the accessibility of feature significantly influence the precedence relations.

Before defining feature accessibility, the following concepts are introduced first:

- ***Tool Access Direction (TAD)*** it is an unobstructed direction from which a cutting tool can access to remove a simple machining volume
- ***Opening Face of Feature (OpF)*** it is an imaginary face of the feature, and its normal vector is opposite to its Tool Access Direction.

- ***Tool Accessibility*** is the constraint for interference between the approaching tool and all other feature volumes. Usually ray-casting test is used.

Definition 1 - Tool Accessibility: A feature is tool accessible only when the tool can access it from at least one of its opening faces.

Definition 2 - Feature Exposition: A feature is exposed only when all its imaginary faces are exposed.

Definition 3 - Feature Accessibility: A feature is accessible only when it is "feature exposed" and "tool accessible".

These definitions determine the accessibility of the feature. The sequence of features being produced determines the sequence of faces of features being exposed. The real faces of a feature are produced or exposed by machining of the feature while its imaginary faces are not. The imaginary faces of a feature could be produced from the machining of other features or already existed on the blank of the part. Therefore, The M-R face dependency between an imaginary face of a feature and a real face of another feature that produces it has great influence on generating feature geometric precedence relations. That is to determine which real face of a feature obstructs an imaginary face of another feature.

4.2 Feature Precedence Relations

Besides the feature geometric precedence, there are reference precedence and other kinds of precedence due to good manufacturing practice. Therefore, we classify the precedence relations into following three categories:

(1) ***Geometric precedence*** – determined by the Definition 1 – Tool Accessibility and Definition 3 – Feature Accessibility described in section 4.1.

(2) ***Reference precedence*** – determined by tolerance datum surfaces and/or elements that are references between different features such as real faces (never be an imaginary faces) of a feature or centerline of a hole.

(3) ***Machining expertise precedence*** – determined by good manufacturing practice accumulated from experience and special knowledge. For examples, maximum material removal volume for rough milling, tool compatibility - features that have the same radius and are accessible by the same tools, and a hole in an oblique face - drilling the hole before machining the oblique face.

Due to the complex designs of today's products and various machining techniques, conflicts may occur between different kinds of feature precedence. Resolving these potential conflicts will be the ongoing research of this project and their methodologies will be published in due time.

5. Case Study For Representation of Feature Precedence Relations

Following examples are given to illustrate the representations of interactions and precedence relations between features.

5.1 M-R Face Dependency

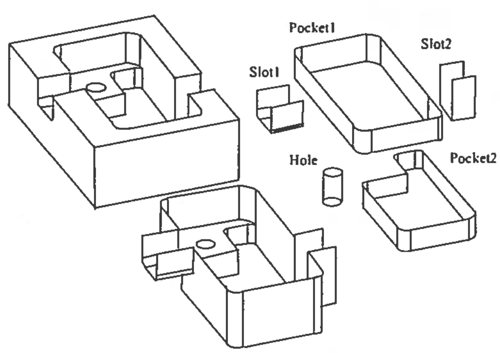


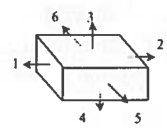
Figure 4. Feature-based Part Model

In Figure 4, the part has 5 interactive features - 2 through slots, 2 pockets and a through hole [8]. It is represented as the feature-based part model proposed in section 3 for feature machining precedence reasoning.

The M-R face dependency is listed in Table 1. It describes whether a real face of a feature will obstruct an imaginary face of another feature. A cube in Table 1 with number 1, 2, 3, 4, 5 and 6 is used to illustrate the six TADs of the part. For each feature, it has a Feature Exposition Flag (FEF) to indicate whether the feature is exposed or not. And for each imaginary face of the feature, it has an iMaginary-Face Exposition Flag (MEF) to indicate whether the imaginary face is exposed or not. If an imaginary face of a feature is a portion of boundary surface of RPT, then set its MEF to Yes, otherwise set to No.

If an imaginary face of a feature is obstructed by a real face of another feature, attach it with an M-R coverage flag (M-RC) and set its initial value to No. For example, the real face R2 of pocket1 obstructs the imaginary face M1, then attach it with a M-RC flag and set its initial value to No.

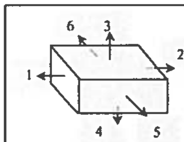
Table 1. M-R Face Dependency

	Slot1 FEF (N)	Slot2 FEF (N)	Pocket1 FEF (Y)	Pocket2 FEF (N)	Hole FEF (N)
	M1 (MEF /Y) M2 (MEF /N) M3 (MEF /Y)	M1 (MEF /N) M2 (MEF /Y) M3 (MEF /Y)	M3 (MEF /Y)	M3 (MEF /N)	M3 (MEF /N) M4 (MEF /Y)
Slot1 (R4, R5, R6)					
Slot2 (R4, R5, R6)					
Pocket1 R1 R2 R4 R5, R6	R1-M2 (M-RC /N)	R2-M1 (M-RC /N)		R4-M3 (M-RC /N)	R4-M3 (M-RC /N)
Pocket2 R2 R1, R1' R4, R5 R6, R6'		R2-M1 (M-RC /N)			
Hole (R 1, 2, 5, 6)					

When one feature is machined, it will expose or partly expose some imaginary faces of other features and change its corresponding M-RC flags to Yes. For each imaginary face, when all its related M-RC flags are set to Yes, that means the imaginary face is exposed completely and set its MEF flag to Yes. When all the imaginary faces of a feature are exposed, the feature is exposed and its FEF is set to Yes.

For example, after the pocket1 is machined, set all M-RC flags in row of pocket1 to Yes. When all related M-RC flags of an imaginary face are set to Yes, set its MEF to Yes. When all MEF flags of a feature are set to Yes, set its FEF to Yes. The updated M-R face dependency after machining the pocket1is listed in Table 2.

Table 2. Updated M-R Face Dependency after Machining the Pocket1

	Slot1 FEF (Y)	Slot FEF (N)	Pocket1 FEF (Y)	Pocket2 FEF (Y)	Hole FEF (Y)
	M1 (MEF /Y) M2 (MEF /Y) M3 (MEF /Y)	M1 (MEF /N) M2 (MEF /Y) M3 (MEF /Y)	M3 (MEF /Y)	M3 (MEF /Y)	M3 (MEF /Y) M4 (MEF /Y)
Pocket1 R1 R2 R4 R5, R6	R1-M2 (M-RC /Y)	R2-M1 (M-RC /Y)		R4-M3 (M-RC /Y)	R4-M3 (M-RC /Y)
Pocket2 R2 R1, R1' R4, R5 R6, R6'		R2-M1 (M-RC /N)			

5.2 TOOL ACCESSIBILITY PRECEDENCE CONSTRAINTS

For the part in Figure 4, the tool accessibility precedence constraints is listed in Table 3, which describes the interference between the approaching tool and all feature volumes. Since a feature can have different TADs, for each TAD of a feature, two kinds of flags are required to determine whether the feature is tool accessible or not. One flag is Identical Setup Direction Flag (ISDF) and the other one is Tool Open Space Flag (TOSF). If one TAD of a feature has the same direction with setup direction, then its ISDF is set to Yes. The TOSF is used to determine the tool interference with other feature volumes. For each feature, a Clear Space Flag (CSF) is used to indicate whether the feature prevents the tool from approaching another feature. A feature could have multiple CSFs. After the feature is machined, set its corresponding CSFs in its row to Yes. When all flags of CSF in the column of a feature's TAD are set to yes, then the TOSF of the feature is set to Yes.

For examples, if TAD3 is selected as setup direction, then all ISDFs of features with the same TAD as TAD3 are set to Yes, otherwise set to No. After the pocket1 is machined, its corresponding CSFs for hole in TAD 3 and for pocket2 in TAD3 are set to Yes. Hence, the TOSF of the hole in TAD3 and the TOSF of pocket2 in TAD3 are set to Yes. In Table 3, pocket1 must be machined first to make the clear space for tool accessing the hole and pocket2 from TAD3.

As described in sections 5.1 and 5.2, the feature geometric precedence relations are represented by updated M-R face dependency and tool accessibility constraints, which include the setup direction, updated topologies and interactions among the features. The sequence of features attained their imaginary face exposition and tool accessibility would determine feature geometric precedence relations between them.

Table 3 Tool Accessibility Precedence Constraints

	Hole (TAF /N)		Pocket1 (TAF /N)	Pocket2 (TAF /N)	Slot1 (TAF /N)	Slot2 (TAF /N)
	TAD3 ISDF (Y) TOSF (N)	TAD4 ISDF (N) TOSF (Y)	TAD3 ISDF (Y) TOSF (Y)	TAD3 ISDF (Y) TOSF (N)	TAD3 ISDF (Y) TOSF (Y)	TAD3 ISDF (Y) TOSF (Y)
Hole						
Pocket1	CSF (N)			CSF (N)		
Pocket2						
Slo1						
Slot2						

5.3 Reference Dependency

The datum reference relations between different features are listed in Table 4.

Critical Tolerance Feature (CTF) set was proposed in [10], which Consists of all the features to be machined in the same setup to attain the required tolerance. And the datum feature should be machined before the measure feature. CTF sets are determined according to the tolerance relationships between all machining features.

In Table 4, the hole1, pocket2, slot1 and slot2 should be grouped into one CTF set and machined in the same setup to attain the required tolerance.

Table 4 Datum Reference Relations

Measure Feature	Datum Feature	Tolerance Type	Tolerance Value (mm)
Hole1	Pocket2	⊥	0.010
Slot1	Slot2	//	0.010
Slot2	Pocket2	⊥	0.060

5.4 Tool Compatibility and Tool Accessibility Direction Compatibility Constraints

5.4.1 Machining Feature Grouping by Tool Compatibility

Besides feature geometry, the cutting tool type is another important information embedded in the feature for sequence generation. Features that have the same tool access direction and the same tool radius and their length-to-diameter ratio fall within a certain interval can be machined in one setup with the same cutting tool to minimize the number of tool changes.

5.4.2 Machining Feature Grouping by TAD Compatibility

The features were grouped into a series of Identical Setup Feature (ISF) sets according to their TADs [10]. Each ISF set consists of all the features with the same TAD and corresponds to the same potential setup. As shown in

Figure 5, if the feature only has one TAD, it is grouped into a single TAD cluster, otherwise into multiple TAD clusters. The features in Figure 4 are grouped into different ISF sets as shown in Figure 6.

The determination of reasonable tool access directions for every feature with multiple TADs in setup planning will be discussed in future publications.

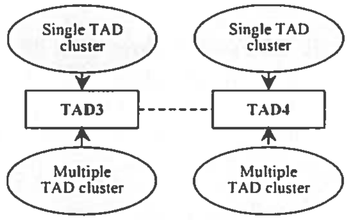


Figure 5. Feature Clusters of ISF Set

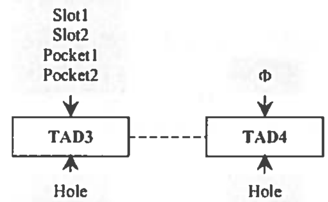


Figure 6. Features Grouped by ISF Set

6. CONCLUSION

This paper presented the definition of feature accessibility and the method to determine the geometric precedence relations. Concepts of setup direction, imaginary face, real face, M-R face dependency and tool accessibility were introduced and discussed. The method developed will contribute to computer aided process planning for CNC programming.

Future extension of this research work will include setup planning, feature sequencing and resolving potential precedence conflicts.

REFERENCES

[1] *Case, K, and Wan Haurun, W. A., " Feature-based representation for manufacturing planning", International Journal of Production Research, Vol.38, No.17, pp.4285-4300, 2000.*

[2] *Gindy, N. N. Z., "A hierarchical structure for form features", International Journal of Production Research, Vol. 27, No. 12, pp.2089- 2103, 1989.*

[3] *Gupta, S. K., Nau, D., REGLI, W. and Zhang, G. M., " A method for systematic generation and evaluation of alternative operation plans", In J. Shah et al. (eds.), Advances in Feature Based Manufacturing (Amsterdam: Elsevier), pp. 161- 184, 1994.*

[4] *Joshi, S., "Feature recognition and geometric reasoning for some process planning activities", In M. J. Wozny et al. (eds.), Geometric Modeling for Product Engineering (Amsterdam: North-Holland), 1990.*

[5] *Kim, Y. S, Wang, E. and Rho, H. M.,"Geometry-based machining precedence reasoning for feature-based process planning", International Journal of Production Research, Vol. 39, No.10, pp.2077-2103, 2001.*

[6] *Kailash, S. B. and Zhang, Y.F., "A volume decomposition approach to machining feature extraction of casting and forging components", Computer-Aided Design, Vol.33, pp.605-617, 2001.*

[7] *Chang, Tien-Chien,* "Expert Process Planning for Manufacturing", Addison-*Wesley Publishing Co., Reading, Massachusetts, 1990.*

[8] *Van Houten, F. J. A. M, van't Erve, A. H. and Kals, H J. J., "PART, a feature based computer aided process planning system", Proceedings of the 21st CIRP Seminar on Manufacturing Systems, Vol. 19, No.1, pp. 25-39, 1990.*

[9] *Wang, L., Cai, N., Feng, H.-Y. and Shen, W., "Feature-Based Reasoning for Machining Process Sequencing in Distributed Process Planning", Proceedings of 13th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM 2003), Vol.2, pp.655-667, 2003.*

[10] *Wu, Y., Gao, S., Chen, Z., "Automatic Setup Planning And Operation Sequencing For Satisfying Tolerance Requirements", DETC2001/DFM-21174, Proceedings of DETC'01 ASME 2001 Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Pittsburgh, Pennsylvania, September 9-12, 2001*

[11] *Yeung, M., "Intelligent Process Planning System for Optimal CNC Programming – A Step Towards Complete Automation of CNC Programming", Proceedings of the International Conference on Manufacturing Automation (ICMA 2002), Hong Kong, China. ISBN: 1-86058-376-8, pp.169 – 177, December 10 – 12, 2002.*