Intelligent Case Retrieval and Modification for Machining Process Planning of Axisymmetric Parts

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Abstract

This research focuses on the development of a retrieval and modification system for reusing a machining process plan of an axisymmetric part for a new part. The proposed system is capable of retrieving the most relevant case of which the finished part is similar to the new desired part, and then modifying the retrieved case to meet the new requirements. The system uses a feature-based representation scheme to represent mechanical parts and processes. According to the cutting process of a part, two kinds of indexes: two-dimensional indexing and feature indexing, are used to organize the case library, and a hierarchical structure of cutting processes is employed to store the cutting history of previous cases. Based on the part representation, indexes, and the hierarchical structure, an effective similarity metric which incorporates geometric shape, material, precision, and cutting process is developed to retrieve the most similar case from the case library. In addition, a modification mechanism is provided to modify the retrieved case. The system is implemented on a Sun workstation using ACIS geometric modeler and C++.

Introduction

A machining process plan of a part contains a sequence of cutting operations, which includes machining cutting (such as turning, drilling) and non-machining cutting (such as heat-treatment), to fabricate the part. Generally, process planners generate process plans of new parts by being reminded of past similar parts, and then modify them to satisfy the new requirements. In fact, it is more efficient for the process planning system to reuse the past successful plans than to start from scratch. Thus, the objective of this research is to develop such an automated process planning system which is capable of retrieving the most similar case effectively and rapidly, and modifying the retrieved case to satisfy the requirements of a new part. The prototype of a retrieval and modification system of process planning for machining of axisymmetric parts is developed.

Previously, two process planning systems CAPLAN/CBC (Muñoz-Avila & Hüllen 1995; Muñoz-Avila, Paulokat, & Wess 1995; Muñoz-Avila & Weberskirch 1996) and PROCASE (Yang, Lu, & Lin 1994; Yang & Lu 1996) have been developed in this domain. The CAPLAN/CBC assumes that the outlines of a final part can be divided into three areas (two rising and one horizontal areas) in the axial direction and each area is machined independently. In practice, these areas are not independent to each other in the machining process. Besides, their retrieval strategy considers only the dimensions of parts. Precision and material of parts are ignored. In fact, both properties are important factors affecting the selection of cutting tools and the construction of the machining process. On the other hand, a part in PROCASE system is represented by using a feature-based representation scheme, and the similarity of two corresponding features is considered only as matched or unmatched. In fact, two different features can be related from their cutting process history. Therefore, the similarity of two corresponding features should be dependent on the degree of difficulty of transforming from one feature to its corresponding feature. In this paper, a feature-based representation, two kinds of indexes (2-D peripheral indexing and feature indexing), and a hierarchical structure of cutting processes are introduced. All features in a axisymmetric part are considered dependently, and their geometries are related in the cutting processes. Based on the indexes and the hierarchical structure, a similarity metric is developed. The system incorporates not only the information of geometric shape, precision, and material, but also the history of cutting process. Because the retrieved case rarely satisfies all specifications of the new part, the system provides a modification mechanism to modify it.

The feature-based representation of parts and processes is presented in Section 2. Case indexing and a hierarchical structure of cutting processes is discussed in Section 3. Precision and material properties are introduced in Section 4. Retrieval techniques and similarity metric are discussed in Section 5. Modification of a process is investigated in Section 6. Section 7 contains

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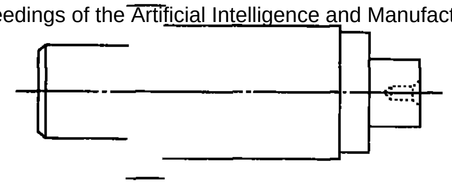


Main-string: PD02_PD91_PD78_PD78_PD18_PX82
Sub-string: Hardness 180, Heat-treatment Norm.

Figure 1: Part representation

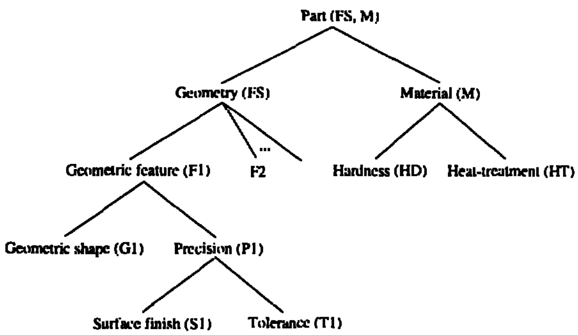


Figure 2: The hierarchical representation

an application example. Conclusions and suggestions for future work are included in Section 8.

Feature-based Representation

Part Representation

In the past, the feature-based representation scheme has been successfully applied to represent mechanical parts (Unger & Ray 1988; Juri & Pennington 1990). It is used here to represent the axisymmetric mechanical parts. Each part is represented by a feature code in the cutting operation. Generally, each part is made of same material, and composed of many geometric features. Each geometric feature stores its corresponding geometric data, such as geometric shape, tolerance, and surface finish. Hence, the feature code for a part consists of a ***main-string*** and a ***sub-string.*** The main-string refers to geometric features of the part along its axial direction. The sub-string consists of hardness, heat-treatment, and other material properties. An example of part representation is shown in Figure 1.

Hierarchical Representation

Besides the part representation in feature string, a part can be specified completely by a hierarchical representation of three major perspectives -- geometric shape, material and precision. The structure of hierarchical representation is shown in Figure 2. In the first level of the proposed hierarchical structure, a part can be represented by: geometry (FS) and material (M). The geometry of a part is a set of geometric features, F_i (i=1,2,...,n), that comprises the part. Each geometric feature contains the information of its geometric shape (G_i) and precision value (P_i). The precision concerns mainly with surface finish (S_i) and tolerance (T_i) of a geometric feature. On the other hand, the material of a part is further decomposed into hardness (HD) and heat-treatment (HT). Thus, a complete specification of a part is $Part = (\{(G_1,(S_1,T_1)), (G_2,(S_2,T_2)), ... \}, \{HD,HT\})$.

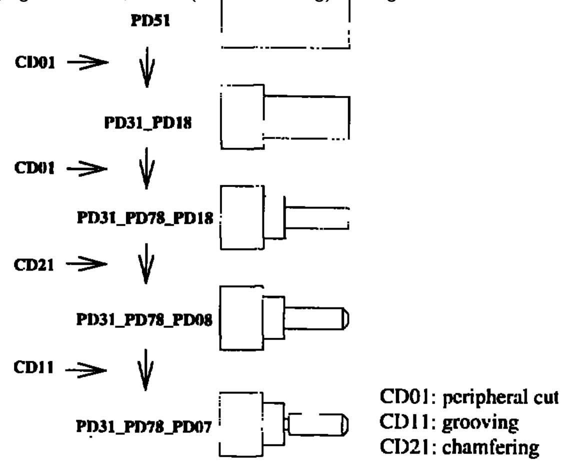


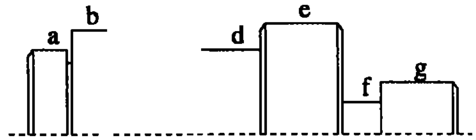
Figure 3: Case representation

Case Representation

A process plan case is a data file which stores the process plan of a part. A data file contains the procedure of how a raw material is manufactured into the final product. The procedure includes material and non-material removal, and each removal step is composed of an antecedent part, a descendent part, and a cutting operation. An example of case representation is shown in Figure 3.

Case Indexing

In the manufacturing of axisymmetric parts, a machining procedure consists of several cutting steps which remove the material from the blank stock by means of different cutting tools. Generally, a part is not produced feature by feature. Contrarily, the cutting procedure of an axisymmetric part is based on the diameter of each feature. The cutting procedure of a part includes coarse cutting and finish cutting. A coarse cutting operation is defined as a peripheral cutting, and the sequence of coarse cutting operations is based on the diameter of each feature. The sequence of finish cutting operations is to produce the final features of a part. According to the coarse cutting and the finish cutting, two kinds of indexes, 2-D peripheral indexing and feature indexing, are developed to represent the cutting procedure of a part.



2-D indexing of the part: 3-2-1-3-2-4-3

Figure 4: A 2-D peripheral indexing

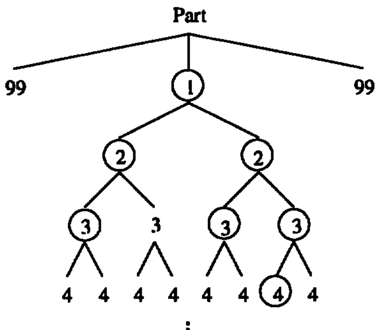
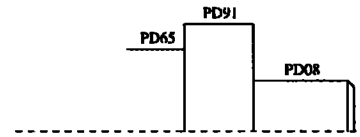


Figure 5: 2-D tree pattern corresponding to 3-2-1-3-2-4-3

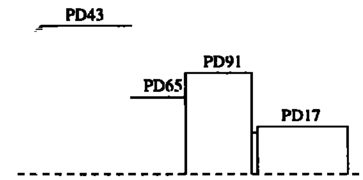
2-D Peripheral Indexing

From the manufacturing point, an axisymmetric part is usually produced based on the diameter of each feature. For instance, considering a part in Figure 4, Feature e must be produced prior to Features d, f, and g. Furthermore, Feature g must be produced prior to Feature f. However, Feature d does not need to be produced prior to Feature g because they are not neighbors. Based on the above observation, a 2-D peripheral indexing is developed to represent the sequence of coarse cutting operations of a part. In the 2-D peripheral indexing, each feature is represented by an digit which indicates its cutting priority in the cutting procedure. The smaller an digit is, the earlier the corresponding feature is machined. For example, the 2-D peripheral indexing of the part in Figure 4 is 3-2-1-3-2-4-3. Feature c is machined first, then Feature b or Feature e, etc. A drill could be applied at one end of a part. Because a drill doesn't affect the other features, 99 is used to represent the drill.

A 2-D tree pattern is used to denote the 2-D peripheral indexing. By marking the corresponding digit in the 2-D tree pattern with respect to each digit in the 2-D peripheral indexing, the marked pattern represents the sequence of the coarse cutting of a part. Figure 5 shows the marked 2-D tree pattern corresponding to "3-2-1-3-2-4-3". Once the marked 2-D tree pattern of a part is done, the similarity measure of the sequence of coarse cutting operations between two parts is computed based on the number of common marked digits shared between two parts. The more the number of



Old part: PD31_PD65_PD91_PD08
2-D indexing: 1-3-2-3



New part: PD43_PD65_PD91_PD17
2-D indexing: 1-3-2-3

Figure 6: The parts with the same 2-D peripheral indexing

common marked digits, the more similar the sequences of coarse cutting operations of two parts.

Feature Indexing

Indexing of a Feature. The 2-D peripheral indexing provides the strategy of computing the similarity measure about the sequence of coarse cutting operations between two parts, but it is not sufficient to compute the similarity between two features. For example, considering two parts in Figure 6, both parts with the same 2-D peripheral indexing have different geometric features. Therefore, when computing the similarity of two corresponding features, the transformation of one feature to another one from the viewpoint of machining processes is needed to be considered. In this respect, a feature indexing for each feature of an old part is developed and extracted from the cutting procedure of the part. For a new part, each feature indexing can be extracted based on the cutting history of all cases stored in the case library since the cutting procedure of the new part is unknown. By combining all the related cutting operations extracted from the cutting history of all cases, a reasonable feature indexing representing the sequence of cutting operations of each feature of a new part can be obtained. To compare a feature of an old part with one of a new part means to compare the corresponding feature indexes of both features. In previous case, for example, PD08 of the old part is compared with PD17 of the new part based on the 2-D peripheral indexing. If PD08 is derived from PDx, and PDx is derived from PDy according to the cutting procedure of the old part, the feature indexing of PD08 should be PDy → PDx → PD08. From the cutting history of all cases, if Case A has a cutting operation (PDy → PD17), and Case B has a cutting operation (PDz → PDy), the feature indexing of PD17 should be PDz →

PDy → PD17. Therefore, the similarity between PD08 and PD17 is the result of comparing PDy → PDx → PD08 with PDz → PDy → PD17. Because these two feature indexes have one common feature PDy, the similarity between feature PD08 of the old part and feature PD17 of the new part is based on the number of steps from PD08 to PD17 through PDy. That is to fabricate PD17 one has to eliminate PDy → PDx → PD08 from the old case and add PDy → PD17 to the old case. A hierarchical structure of cutting processes is used to store all the cutting operations from previous cases.

A Hierarchical Structure of Cutting Processes. The hierarchical structure of cutting processes is extended dynamically according to the changing case library. An edge in the hierarchical structure presents a cutting fact which represents that a child node (descendent feature) can be produced by employing one cutting operation in the parent node (antecedent feature) in which the diameter of the descendent feature is the same as that of the antecedent feature. Assume a cutting procedure of a part is shown in Figure 3. After the first cutting operation is applied in the blank stock, the original part, PD51, becomes a semi-finished part, PD31_PD18. Since 1) PD51 is an active feature on which the cutting operation is applied, 2) PD31 is derived from PD51, and 3) the diameters of PD51 and PD31 are the same, a cutting fact, PD51→PD31, is established. Similarly, another three cutting facts, PD18→PD78, PD18→PD08, and PD08→PD07, are also established from this case. Therefore, four cutting facts are generated from this case and stored in the hierarchical structure. The more the cases are stored in the case library, the more robust the hierarchical structure is.

Precision Property and Material Property

As mentioned earlier, three key factors (geometric shape, material and precision) affect the cutting process of a part. Precision and material are described in the following.

Surface Finish

The surface finish can be further categorized into several groups ranging from very fine to very rough according to the cutting process and machine tools. If the surface finishes of two geometric features are located in the same group, it usually indicates that the cutting processes and machine tools are the same for both features. Therefore, two geometric features with the similar surface finish should be more similar than those whose surface finishes are quite different. Based on that, the similarity of different surface finishes ($S_{surface-finish}$) can be defined, such as 0.3 or 0.5.

Tolerance, Heat-treatment, and Hardness

Likewise, tolerance, $S_{tolerance}$, is divided into several ranges from very tight tolerance to very loose tolerance. Heat-treatment and hardness are also categorized into several groups.

Retrieval

Similarity Metric

A similarity metric is defined based on geometric shape, material, and precision in terms of 2-D peripheral indexing and feature indexing.

$$\textbf{\textit{Similarity}} = \mathbf{W_f}\frac{\sum_{i=1}^{k} match(D_{oi}, D_{ni})}{(D_o + D_n)/2} + \mathbf{W_m}\frac{\sum M_{si}}{\sum M_i} \quad (1)$$

The first term in Equation 1 represents the geometric comparison between two parts. The second term represents the material comparison.

1. $\mathbf{W_f}$ and $\mathbf{W_m}$ are the weighting factors corresponding to the geometric features and material. The summation of these two weights is equal to one. Normally, the geometric features will carry more weight than material since geometric similarity is more important for retrieving the most similar part.
2. $\sum_{i=1}^{k} match(D_{oi}, D_{ni})$ is the geometric similarity (including geometric shape, surface finish, and tolerance) of two compared parts according to the 2-D peripheral indexing and the feature indexing. k is the total number of common digits shared between two parts.
3. $(D_o + D_n)$ is the total number of features in both 2-D peripheral indexes of compared parts.
4. $\sum M_{si}$ is the summation of heat-treatment similarity value and hardness similarity value between two parts.
5. $\sum M_i$ is the total number of material properties. Because only heat-treatment and hardness are considered here, this term is equal to 2.

Geometric Similarity Based on 2-D Peripheral Indexing and Feature Indexing

An example in Figure 7 is utilized to explain how to define the geometric similarity. Assuming the case representation of Case 1 is shown in Fig 7.a, and the main-string of part 1 (the finished part of Case 1) is PD31-PD07. The new desired part is shown in Fig 7.b and its main-string is PD43-PD08. All cutting facts extracted from several cases of cutting process plans are established in the hierarchical structure of cutting processes in Fig 7.c. Based on the diameter of each feature of part 1 and the new part, the 2-D peripheral indexing for both parts is "1-2". Therefore, both D_o and D_n defined in the last subsection are equal to 2, and PD31 is compared with PD43 and PD07 is compared with PD08. $\sum_{i=1}^{k} match(D_{oi}, D_{ni})$ becomes $match(PD31, PD43) + match(PD07, PD08)$.

When comparing two geometric features, not only geometric shape, but also surface finish and tolerance are

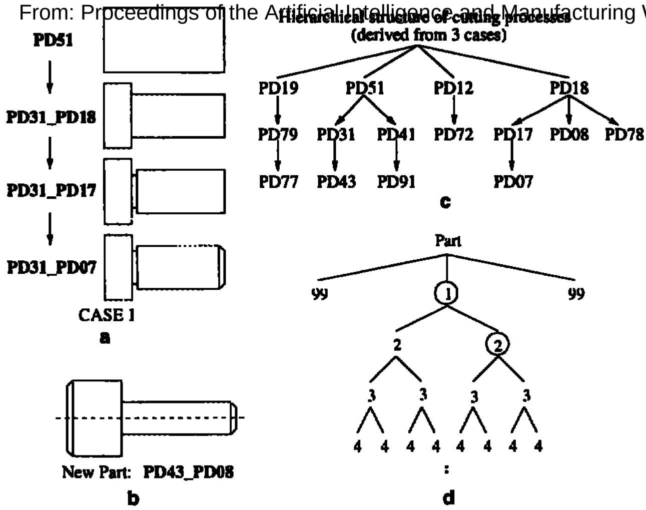


Figure 7: Geometric similarity

considered. Besides, the comparisons of surface finish and tolerance between two parts are meaningful, only if the comparison of geometric shape between two parts is not equal to zero. Therefore, $match(D_{oi}, D_{ni})$ can be defined as

$$match(D_{oi}, D_{ni}) = \frac{S_{surface-finish} + S_{tolerance}}{2} \times S_{geom-shape} \quad (2)$$

Based on the surface finish and tolerance described before, $S_{surface-finish}$ and $S_{tolerance}$ can be computed. In addition, it is mentioned in previous section that the similarity of geometric shape between two features is mainly dependent on how to delete extra cutting operations from the retrieved case and insert additional cutting operations into the retrieved case. In this example, the feature indexing for each feature of part 1 is

PD51→PD31,
PD18→PD17→PD07.

From the hierarchical structure (Fig 7.c), the feature indexing for each feature of the new part is:

PD51→PD31→PD43,
PD18→PD08.

Therefore, To compare PD31 with PD43, we should compare the feature indexing of PD31 and the feature indexing of PD43 to find out the common feature which is nearest to both corresponding features. In this case, PD31 is the common feature for PD31 and PD43. Similarly, the common feature for PD07 and PD08 is PD18. It also means to transform PD31 to PD43, an additional operation (PD31→PD43) should be added in the retrieved case. Similarly, to transform PD07 into PD08, two cutting operations (PD18→PD17 and PD17→PD07) should be deleted and one additional operation (PD18→PD08) should be added. If no common feature exists, it means one feature can not be transformed into another feature based on the cutting history of stored cases. According to the above description, $S_{geom-shape}$ can be defined as

$$S_{geom-shape} = \mathbf{W_o}\frac{(T_o - L_o)}{T_o} + \mathbf{W_n}\frac{(T_n - L_n)}{T_n} \quad (3)$$

where the first term is to describe the elimination of operations, and the second term is to describe the addition of operations. W_o and W_n are weighting factors corresponding to the elimination and the addition. Generally, W_n is greater than W_o because deleting one cutting operation from the retrieved case is much easy than adding one from another case. T_o is the total number of features in the feature indexing of the corresponding feature of the old part, and T_n is the total number of features in the feature indexing of the corresponding feature of the new desired part. L_o means the number of cutting operations should be deleted and L_n means the number of cutting operation should be added. Equation 3 shows that the less elimination (or addition) applied, the larger the similarity measure. Because these $S_{geom-shape}$ values are useful for the modification, they are kept as well as the similarity value after retrieval.

Modification

Generally, because the retrieved case rarely meet all specifications of the new part exactly. it must be modified. There are four main types when the 2-D indexing of the retrieved part is compared with that of the new part: 1) 2-D indexes of the retrieved part and the new part is exactly the same. 2) the retrieved part has extra geometric features which are not in the new part, 3) the retrieved part has missing geometric features relative to the new part, and 4) the retrieved part has extra geometric features and missing geometric features. Furthermore, according to the feature indexing, the corresponding geometric features of the retrieved part and the new part may not match each other for all four types. Therefore, the modification for each type are described as follows.

Type 1) If the corresponding features are not matched, the feature modification should be applied.

Type 2) According to the definition of the 2-D indexing, once the retrieved part has extra features, its 2-D indexing will also have the corresponding extra digits. Based on this information, the cutting processes for creating those extra features can be easily eliminated from the the retrieved process plan.

Type 3) When the retrieved part has missing features, it means the 2-D indexing of the new part has extra digits. By clustering the adjacent extra digits into one group, one or several clustered groups will be generated to cover all extra digits. Because each digit represents one feature and the two neighboring digits of each clustered group are the bridge between the clustered group and the 2-D indexing, "neighboring digit + clustered digits + neighboring digit" can be considered as a sub-part. For instance, assume that the 2-D indexes of the retrieved part and the new part are 2-1-2-3 and 2-4-3-1-2-4-3, respectively. The missing features for the retrieved part are 4-3 and 4, therefore, two sub-parts will be generated and their corresponding 2-D indexes are 2-4-3-1 and 2-4-3. Because the smallest digit in 2-4-3 is not equal to 1, we can rewrite it as 1-3-2 by subtracting 1 from each digit. Finally, two sub-parts are created in this example and their corresponding 2-D indexes are 2-4-3-1 and 1-3-2. After that, to find the processes for missing features will be similar to find the processes for sub-parts. Therefore, the procedure of retrieval and modification is called recursively until all sub-parts are resolved.

Type 4) Actually, it is the combination of Type 3 and Type 4. Thus, the solutions for types 3, 4 are applied here.

Feature modification) If two corresponding feature are unmatched for the above types, the further modification between these two feature is needed. In fact, once the similarity between the retrieved part and the new part is computed, the information about how to transform features of the retrieved part to the corresponding features of the new part will be available. That is, if the $S_{geom-shape}$ between two features is

1) > 0: the information in which cutting operations should be eliminated from the cutting history of the retrieved part and cutting operations should be inserted from the hierarchical structure of cutting processes will be used. Thus, the corresponding feature in the retrieved part can be transformed to the desired feature in the new part.

2) $= 0$: the relation between two features does not exist. When this case happens, the relative information can be added by users.

The above discussion leads to the following modification algorithm:

- Modification Algorithm
  1. If k (in Equation 1) is equal to both the number of features in the retrieved part and the number of features in the new part, then goto Step 5.
  2. If k is equal to the number of features in the new part, it means that the retrieved part has more features than the new part. Perform Elimination Algorithm, and then goto Step 5.
  3. If k is equal to the number of features in the retrieved part, it means the new part has more features than the retrieved part. Perform Addition Algorithm, and then goto Step 5.
  4. If k is smaller than both the number of features in the retrieved part and the number of features in the new part. Perform Elimination Algorithm and Addition algorithm.
  5. If several $S_{geom-shape}$ values are not equal to 1, then perform Transformation Algorithm. Otherwise, terminate.
- Transformation Algorithm
  If $S_{geom-shape} = 0$, then users are asked to enter the relative cutting information. Otherwise, according to the feature indexes of both unmatched features, find out the common feature which is nearest to both unmatched features. Eliminate those cutting operations which create the feature in the retrieved part from the common feature, and insert cutting operations which will create the corresponding feature in the new part from the common feature.
- Elimination Algorithm
  Trace back the cutting process of the retrieved part. Mark those cutting operations which create the extra features, and then eliminate them.
- Addition Algorithm
  As mentioned earlier in this section, generate sub-part(s) based on those missing features and their neighbor features, and then perform retrieval algorithm and modification algorithm for each sub-part.

An Application Example

In this study, forty five basic geometric features, have been implemented in our system for design, retrieval, and evaluation. Five parts with successful process plan are created for testing purpose in this example. These parts and a new desired part are displayed in Figure 8, and their feature codes are listed as following.

part 1) main-string: PX81-PD12-PD72-PD91-PD18-PX82,
sub-string: HD 200, HT Ann.
part 2) main-string: PD31-PD77-PD07,
sub-string: HD 250,HT Norm.
part 3) main-string: PD43-PD78-PD08-PX82,
sub-string: HD 200, HT Ann.
part 4) main-string: PD02-PD44,
sub-string: HD 280, HT Norm.
part 5) main-string: PD02-PD91-PD77-PD08-PX82,
sub-string: HD 300, HT Ann.
new part) main-string: PD02-PD91-PD08-PX82,
sub-string: HD 180, HT Ann.

W_f, W_m, W_o, and W_n defined in Equations 1 and 3 are assumed to be 0.65, 0.35, 0.3, and 0.7, respectively. In addition, all of tolerances of the new desired part are assumed to be 0.005 (in) and surface finishes are assumed to be 64 (μin).

Plan Retrieval

According to the cutting processes of five cases, a hierarchical structure of cutting processes is constructed automatically by the system and is depicted in Figure 7.c. The calculation of the similarity measure between **Part 1** and the **new part** is explained as follows.

Step 1) All the tolerances of **Part 1** are assumed to be 0.01 (in), and surface finishes are assumed to be 80 (μin). Based on the diameter of each feature, the 2-D peripheral indexing for **Part 1** is 99-3-2-1-2-99 and 2-1-2-99 for the **new part**. From the cutting

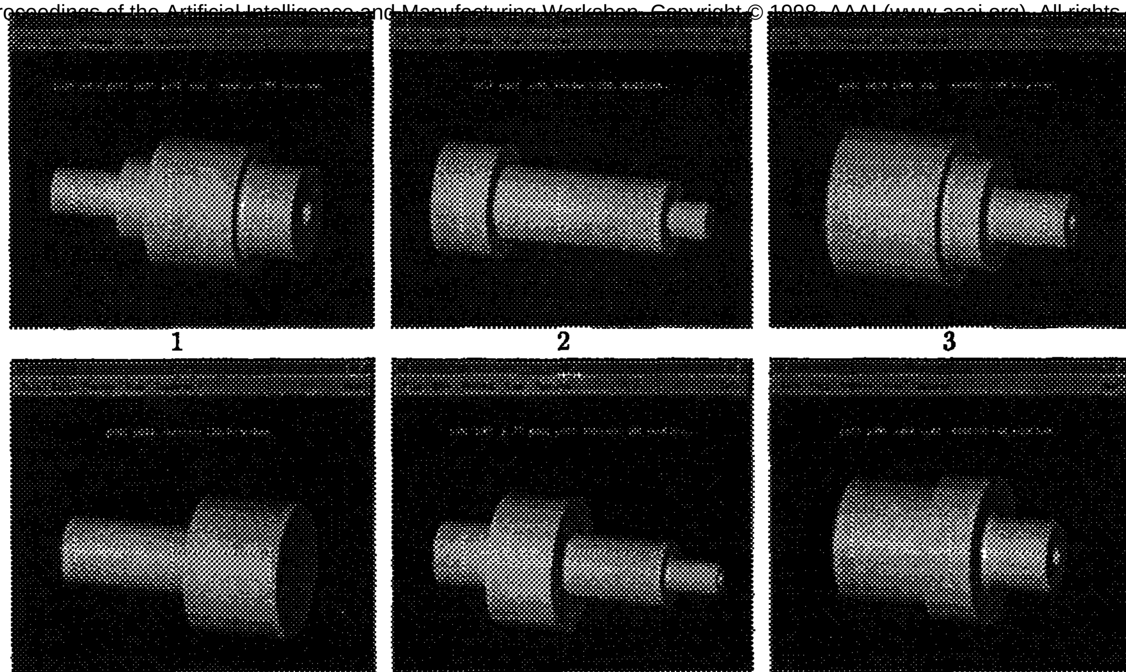


Figure 8: Five cases in case memory and a new desired part

procedure of **Part 1**, the feature indexing for each feature is

PX81,
PD12,
PD12→PD72,
PD51→PD41→PD91,
PD18, and
PX82.

From the hierarchical structure of cutting processes, the feature indexing for each feature of the **new part** is

PD12→PD02,
PD51→PD41→PD91,
PD18→PD08, and
PX82.

From the 2-D peripheral indexing, $\sum_{i=1}^{k} match(D_{oi}, D_{ni}) = match(PD72, PD02) + match(PD91, PD91) + match(PD18, PD08) + match(PX82, PX82)$.

According to the surface-finish, tolerance, and Equation 3, $\sum_{i=1}^{k} match(D_{oi}, D_{ni}) = 2.757$.

Step 2) $(D_o + D_n)/2 = (6+4)/2 = 5$

Step 3) According to heat-treatment and hardness information, $\sum M_{si} = 1.75$.

Step 4) $\sum M_i = 2$. (including 2 items: Heat-treatment and Hardness)

Step 5) According to Equation 1, the similarity of **Part 1** and the **new part** is 0.665

Similarly, the similarity for the other parts will be

Similarity = 0.235 for **Part 2**,

a:

PD51
↓
PD51-PX82
↓
PX81-PD51
↓ eliminated cutting
PX81-PD51-PX82
↓
PX81-PD31-PD18-PX82
↓ eliminated cutting
PX81-PD31-PD78-PD18-PX82
↓
PX81-PD12-PD72-PD41-PX82
↓
PX81-PD12-PD72-PD91-PD18-PX82

b:

PD51
↓
PD51-PX82
↓
PX81-PD51
↓
PX81-PD31-PD18
↓ added cutting
PX81-PD31-PD08
↓
PD02-PD41-PX81
↓
PD02-PD91-PD18-PX82
↓ added cutting
PD02-PD91-PD08-PX82

Figure 9: The retrieved process plan and the modified process plan

Similarity = 0.565 for **Part 3**,
Similarity = 0.481 for **Part 4**,
Similarity = 0.648 for **Part 5**.

Plan Modification

From the above result, **Part 1** is the most relevant part, and its cutting process plan is depicted in Figure 9.a. According the modification algorithm, the elimination algorithm is applied to eliminate features PX81 and

PD12 of **Part 1**, and the transformation algorithm is applied to transform PD72 and PD18 of **Part 1** to PD02 and PD08 of **new part**, respectively. The modified process plan is depicted in Figure 9.b.

Conclusions and Future Works

A retrieval and modification system for machining process plan of axisymmetric parts is presented. The system allows the manufacturers to generate the cutting process plan of the desired part based on the past successful cases. This system consists of two elements: retriever and modifier. The retriever found out the most appropriate one from case library by applying the similarity metric to rank the similarity of all cases. The similarity metric incorporates not only the information of geometric shape, precision, and material, but also the history of cutting process. Furthermore, the modifier compensate for the differences between the retrieved part and the new one. The empirical results shows that the most relevant case can be retrieved and modified effectively, and the procedure of retrieval also provides the information for modification. The system is currently implemented on a Sun workstation using ACIS geometric modeler and C++.

Our future research will focus on two other functionalities: simulation and reparation. These functions are attempted to verify the feasibility of the modified process plan, and to repair the modified process plan if necessary.

Acknowledgments

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