Application of Semantic Feature and Feature Transformation in Generative Process Planning

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Abstract.

This paper reports on the development of a concurrent engineering system which covers four application domains in production of mechanical parts, namely design, manufacturing, assembly and inspection. Two approaches are introduced: 1). semantic feature which describes information within each domain separately, and 2). feature transformation which manipulates and derives information across different application domains. Their applications in generative process planning are illustrated in a case study.

Keywords: *Process planning, CAD/CAPP/CAM integration*

1. Literature Review.

In a concurrent engineering system, it is desirable to provide designers with the most natural design environment and the manufacturing system with the necessary detailed information. One of the most popular approaches in design and manufacturing integration is the feature-based approach. Feature technology has been widely applied in various fields and a number of systems were implemented, for example in feature solid modeling and representation^{[1],[2]}, in process planning^{[3], [4]}, for NC-programming^[5], and in automatic assembly^[6]. The above systems only apply features to the geometric domain. M.R. Cutkosky^[7] proposed a concept for a feature-based generative process planning system covering design, process planning and fixture design and assembly domains without detail discussion. The development of concurrent engineering system requires a systemic and efficient representation for information in different application domains.

In a feature-based system, processes and tools selected and machining parameters derived are usually based on the requirement of features on final product such as in [5], [8] and [9]. The influence of stock on machining processes is generally overlooked. Many researchers address their interest in optimizing manufacturing processes, machining parameters and sequence arrangement^{[10], [11]}. However, few can generate the modeling of intermediate stages of workpiece which is needed to provide information for designing jigs and fixtures for each setup and to develop inspection methodology for quality control during manufacturing.

This paper presents a feature-based concurrent engineering environment and introduces the semantic feature and feature transformation approaches for automated generative process planning.

2. System Overview.

The proposed concurrent engineering system covers most application domains in the production of mechanical parts, such as design, manufacturing, assembly and inspection, etc.. A hierarchical structure of feature is established and information is represented in different domains. Feature transformation is applied to keep system consistent and transfer and derive information from one domain across to another.

As designer creates a product assembly, the proposed system will automatically provide detail description of geometry, material properties, engineering attributes such dimension, dimensional tolerance, surface finishing and geometry tolerance, etc. It will select suitable manufacturing processes and fixtures for each component, and determine assembly tools and sequence for the product with inspection methodology for at both component and assembly levels.

The manufacturing process can be divided into three stages: primary process, secondary process and finishing process. The primary process is the process forming stock, i.e. injection molding, casting and welding, etc.. The secondary process is commonly known as machining process and the finishing process is final step of manufacturing, such as cleaning, smoothness, and painting.

The inspection strategy can be classified into in-line inspection and off-line inspection. In-line inspection, most happened in the secondary process, monitors machining quality during cutting. Off-line inspection is mainly the process of measuring dimension, tolerance and surface finishing of workpiece, component or assembly between each manufacturing setup.

3. Representation of Geometrical Information and Manufacturing Process.

The feature-based system uses a hierarchical structure of feature to represent the geometrical information of the part and its manufacturing information. To describe the methodology applied in process planning more clearly, the concepts of feature, feature classification and feature transformation are introduced briefly in the rest part of this section and details may be found in [12].

The following symbols are used in the feature classification.

::=	: composed by	<< >>	: member of
< >	: content	[]	: constraint

3.1. Features and Feature Classification.

Feature is defined as a group of abstract data with attributes. The abstract data includes the name of the feature and its type which is helpful in identifying corresponding features in various domains. Feature is an abstract class co-ordinating other classes of feature on different levels and in different domains.

Feature has two types of attribute: static attribute and dynamic attribute. Static attributes, or constraints, and its value is not allowed to be changed or modified. For example, subtractive_feature class which is under design_feature, limits that all feature class below it can only be applied to the "difference" Boolean operation. Static feature propagates from high level class to lower level ones with the addition of more detail information. It is valid only within a specified domain and affects feature classes below it. Dynamic attribute, which is opposite to static attribute, allows its value to be changed or modified at any time, e.g. radius and height of a cylinder. As it propagates to detail levels, a dynamic attribute may become a static attribute.

In mathematical format, feature can be written as :

Feature	::=	<Abstract_data> <Attributes> <Concurrent_parameter_list>
Abstract_data	::=	<Feature_name> <Feature_type>
Attributes	::=	<Static_attributes> <Dynamic_attributes>
Concurrent_parameter	::=	<feature_function> <mating_feature> <mating_component>

3.2. Component in Design Domain and Design_features.

As shown in Figure 3.1, a component in design domain is described by a list of design_features and a list of surfaces. The design_feature list includes both topological and geometrical information of feature. The properties of component such as material, hardness are viewed as attributes of the design_feature list. The surface list contains all information on the surfaces in the component model. Pointers are used to link to design_features and the corresponding surfaces. The reference list is an attribute of design_feature and represents relationship between surfaces of this feature with that of others.

Design_feature is a feature with geometrical attributes which are sufficient to describe its shape, orientation, size, roughness, dimensional tolerance and geometry tolerance. Written in mathematical format, it is:

```

Design_feature ::= <<Feature>>
                  <Geometry>
                  <Design_quality>

Geometry ::= <B_rep_object>
             <surface_list> <position>
             <orientation>
             <dimension>
             <geometric_operator>

geometric_operator ::= [Difference || Union ||
                       Intersection || NULL]

Design_quality ::= <dimensional_tolerance> <surface_finishing> <geometry_tolerance>

```

Figure 3.1 Component Representation in Design Domain

3.3. Component in Manufacturing Domain and Manufacturing_features.

In manufacturing domain, a component is described by its manufacturing processes. Primary process is represented by a list of primary_feature, and similarly, secondary process is by a list of secondary_feature and finishing process is by finishing_feature list.

Written in mathematical format, they are:

```

Manufacturing_feature ::= <<Feature>> [PRIMARY || SECONDARY || FINISHING]

Secondary_feature ::= <<Feature>> <Machine_Parameter_List>
Machine_Parameter ::= <tool_name> <setup_data> <machining_operator>
setup_data ::= <power> <spindle_speed> <feed_speed> <cut_depth>
               <set_up_no> <tool_access_direction> <feed_direction> <fixture_code>
machining_operator ::= [Mill || Plane || Drill || Bore || Ream || Grind]

```

Similar syntax is used to define primary_feature, finishing_feature, assembly_feature and inspection_feature [12].

4. Feature Transformation.

Feature transformation is the process of deriving, calculating and manipulating data among different feature classes. It describes the reasoning process about generating machining sequence for a given component, determining the machine setups needed for each intermediate stage, selecting assembly sequence for product designed and arrange on-line and off-line inspection to control quality.

Four operators in feature transformation are identified and presented below. Operands and constraints in operation are discussed in detail in [12].

⊖	: comparison operator	⊕	: reference operator
⇒	: reasoning operator	+*	: group operator

5. Application of Feature Transformation - Generative Process Planning.

Process planning is an activity through which design requirement is satisfied by determining the overall machining sequence and the individual cutting conditions for each machining setup. In the system a final product is represented as a

list of design_features either input manually or retrieved from database. As properties of product, material and its hardness are the attributes of the list. The machining process for the product is a list of secondary_features. The stock is generated by assuming it is a casting with specified machining allowance. Based on the final product and the stock, the machining process is derived. The dimension, tolerance and roughness all have influence on the process plan. There are three kinds of feature transformation developed in generative process planning and are applied in stock generation, machining parameters selection and sequence arrangement, and intermediate stages of workpiece generation respectively.

Figure 5.1 Stock and Part Relation.

5.1 Feature Transformation within Design Domain - Stock Generation.

Written in mathematical formation, the feature transformation is

$$design_feature_final \Rightarrow design_feature_initial$$

As shown in Figure 3.1, the input to the system is the design_feature description of the part. It indicates the final stage of manufacturing process. The task of stock generation is to specify the initial form of the workpiece which is assumed to be sand cast.

Attributes of each design_feature in the part, such as dimensional tolerance, geometry tolerance and roughness, are needed to determine how a feature is formed. For a cast feature, the design_feature should remain identical in the stock to part transmission. For a machined feature, its corresponding design_feature should have the volume of stock larger than that of part. The basic principle for stock generation is the overall volume of stock should not less than that of part. The algorithm for stock generation is presented below.

```

Main :
Begin: for each design_feature in the part list
      check its tolerance and surface finishing
      if needs machining
        generate the design_feature on the stock and put it into stock list
        generate a secondary_feature for it and put into secondary_feature list
      else
        copy the design_feature and put into stock list
      end if
    end for
end Main

```

A secondary_feature list is created to represent machining process resulted from reasoning in later stages. During the stock generation process, usually not only dimension, tolerance and roughness of a design_feature are changed, but also feature type and its geometry may be different and its position may be altered due to variation of other design_features. For example, in Figure 5.1, a through hole in the part (body line area) may become a cast hole in the stock (dot line area). Its shape is a cone rather than a cylinder. The secondary_feature list created here will help in maintaining consistency between stock and part.

5.2. Feature Transformation from Design_feature to Secondary_feature - Machining Parameters Selection and Sequence Arrangement.

The feature transformation can be written in mathematical format as below.

$$design_feature_final \ominus design_feature_initial \Rightarrow secondary_feature$$

Cutting condition is determined for each design_feature in the part that needs to be machined and result is stored in its corresponding secondary_feature. Machining parameters are derived naturally based on the difference between a design_feature in the part and its corresponding one in the stock. All information about tools, cutters, cutting method, etc., is stored in a database. Data is retrieved through knowledge base and according to feature type.

Attributes used and derived in this stage are :

$$B_rep_object(design_feature_final \ominus design_feature_initial) + * dimension(design_feature_final \ominus design_feature_initial) + * dimensional_tolerance(design_feature_final \ominus design_feature_initial) + * surface_finishing(design_feature_final \ominus design_feature_initial) \Rightarrow$$

$$[CAST || MACHINED] machining_operator + * cut_depth + * cut_range + * spindle_speed + * feed_speed + * cutter_name + * power$$

$$orientation(design_feature_final) + * machining_operator \Rightarrow tool_access_direction + * feed_direction$$

$$machining_operator + * cutter_name + * power \Rightarrow tool_name$$

The algorithm for selecting cutting parameter is presented below.

Main:

Begin : for each secondary_feature in the secondary_feature list

 retrieve the design_feature on part

 retrieve the design_feature on stock

 select cutting method

 case :

 1). no method is available
 report error and stop

 2). only one method available
 call select_cutting_parameter

 3). more than one method available
 for each method available
 estimate its cutting time cost
 estimate its tool changing time cost
 end for
 select the method with minimum cost
 call select_cutting_parameter

 end case

end for

end Main

select_cutting_parameter:

Begin: select cut depth, feeding speed, spindle speed, power, cutters

end select_cutting_parameter

The machining sequence is arranged by using minimum setup principle.

5.3. Feature Transformation from Secondary_feature to Design_feature - Intermediate Stages of Workpiece Generation.

The feature transformation can be written in mathematical format as below.

$$secondary_feature \oplus design_feature_previous_setup \Rightarrow design_feature_next_setup$$

As mentioned above, the manufacturing process starts at the stock (initial stage) and ends at the product (final stage). Usually a production has to go through several setups to reach the end and each setup should have a set of fixture. Hence the

information about intermediate workpieces is required. The feature transformation from secondary_feature to design_feature represents the process of generating workpieces for all the intermediate stages of machining setups.

Attributes used and derived in this stage are :

*machining_operator + * cutter + * cut_depth + * cut_range + * spindle_speed + * feed_speed + * set_up_no $\Rightarrow$
B_rep_obj + * face_list + * dimension + * dimensional_tolerance + * surface_finishing*

*position(design_feature_previous_setup) + * orientation(design_feature_previous_setup) $\Rightarrow$
position(design_feature_next_setup) + * orientation(design_feature_next_setup)*

These workpieces actually describe the transition process from stock to product. The algorithm is presented below.

Main:

Begin: for each machine set-up

for each design_feature in previous workpiece list

get its corresponding secondary_feature

get the cut depth of current set-up

re-generate design_feature and put into current workpiece list

end for

end for

end Main

6. System Implementation and Case Study.

Figure 6.1 shows the engineering drawings of an example part, the moving bracket of a pad printing machine. All design requirements such as dimension, dimension tolerance, surface finishing and geometry tolerance are marked clearly. Figure 6.2 gives the isotropic view of the moving bracket and its design_feature list is presented in Table 6.1. Figure 6.3 displays the stock used to get the moving bracket which is gotten through sand casting. And figure 6.4 is part of cutting process required to manufacture the moving bracket. The intermediate stages of manufacturing are shown in from figure 6.5 to figure 6.9.

The system is developed on SUN SPARC 10 platform using CVDORS as a solid modeling tool. The hierarchical structure of feature classes and knowledge base are written in C++. A relational database system SYBASE is used to store tooling information and fixture component library.

No.	Design_feature	No.	Design_feature
01	Primitive Box	11	Boss
02	Boss	12	Through Hole
03	Threaded Hole M8	13	Threaded Through Hole M4
04	Through Hole	14	Tablet
05	Through Hole	15	Threaded Through Hole M4
06	Boss	16	Through Hole
07	Threaded Hole M8	17	Threaded Through Hole M4
08	Pocket	18	Threaded Through Hole M4
09	Full Slot	19	Threaded Hole M8
10	Threaded Hole M8	20	Boss
		21	Through Hole

Table 6.1 Design_feature List of Moving Bracket.

7. Discussion.

The feature transformation approach described above has been used to generate process plans for a final product built from predefined design_features. It is possible to show that a stock can be generated based on the requirements prescribed in the design_features of the product and stock forming process. Different process plans can be generated from the difference between the stock and the product. The machining sequence can be arranged according to the spatial and relative relationships among design_features. Intermediate stages of manufacturing are derived by considering the machining steps in each machining setup.

The hierarchical feature structure provides a scheme to represent information in different application domains (design domain and manufacturing domain) and at different detail levels. The feature transformation method supports an efficient and consistent reasoning process to manipulate attributes of features across application domains.

Further research will be concentrate on the below areas:

- A more general feature transformation scheme should be established to cover a wider range of manufacturing process.
- A more comprehensive sequence arrangement strategy should be provided so that machining sequence can be optimized and manufacturing cost can be minimized.
- For each machining setup, a jigs and fixtures system should be designed automatically by considering the intermediate stage of workpiece and machining activities carried out in the setup.
- For each machining setup, NC cutting path should be generated based on the intermediate stage of workpiece and machining parameter selected.

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Figure 6.1 Engineering Drawing of Moving Bracket.

Figure 6.2 Isotropic View of Moving Bracket.

Figure 6.3 Stock of Moving Bracket.

```

Boss :
Position : 100.000000, -100.000000, 0.000000
Direction : 0.000000, -1.000000, 0.000000
Top Diameter : 50.000000 mm Height : 5.000000 mm
Status : Machined Feature
Tooling Accessing Direction : 0.000000, -1.000000, 0.000000
Feeding Direction : -0.707107, 0.000000, 0.707107
-----
Tool : NO
Cutter : T-MAX_145.R260.22-080-15-V63
Insert : SEKN-12_04_AZ-SMA Number : 6
Cutter Diameter : 80.000000 mm
Cutting Method : rough mill
Power : 6.546533 KW Torque : 153.284678 Nm
Cutting Speed : 102.500000 m/min Spindle Speed : 407.000000 rpm
Feeding Speed : 1.800000 mm/r Cutting Depth : 6.300000 mm
Set-up Sequence : No.4 Fixture Code : not available
Cutting Force : X - 2874.087711, Y - 2203.467245, Z - 2011.861398
-----
Tool : NO
Cutter : T-MAX_145.R260.22-050-15-V50
Insert : SEKN-12_04_AZ-SMA Number : 4
Cutter Diameter : 50.000000 mm
Cutting Method : semifinish mill
Power : 0.258772 KW Torque : 2.822967 Nm
Cutting Speed : 137.500000 m/min Spindle Speed : 875.000000 rpm
Feeding Speed : 0.600000 mm/r Cutting Depth : 0.700000 mm
Set-up Sequence : No.4 Fixture Code : not available
Cutting Force : X - 84.689005, Y - 64.928237, Z - 59.282304
*****
Through Hole :
Position : -100.000000, 105.000000, 0.000000
Direction : 0.000000, 1.000000, 0.000000
Diameter : 30.000000 mm Height : 210.000000 mm
Status : Machined Feature
Tooling Accessing Direction : 0.000000, 1.000000, 0.000000
Feeding Direction : 0.000000, 1.000000, 0.000000
-----
Tool : NO
Cutter : Delta.R411.5-29032_D29.00_zz_P
Insert : NO
Cutter Diameter : 29.000000 mm
Cutting Method : normal drill
Power : 3.674975 KW Torque : 31.080906 Nm
Cutting Speed : 94.000000 m/min Spindle Speed : 1031.000000 rpm
Feeding Speed : 0.400000 mm/r Cutting Depth : 14.500000 mm
Set-up Sequence : No.6 Fixture Code : not available
Cutting Force : X - 0.000000, Y - 0.000000, Z - 9893.540878
-----
Tool : NO
Cutter : T-MAX_U.R479.0-32-2565-11
Insert : TCMT-11_02_02-UF-GC415 Number : 1
Cutter Diameter : 32.000000 mm
Cutting Method : normal bore
Power : 11.906276 KW Torque : 185.880683 Nm
Cutting Speed : 126.825581 m/min Spindle Speed : 1261.000000 rpm
Feeding Speed : 0.275000 mm/r Cutting Depth : 0.500000 mm
Set-up Sequence : No.6 Fixture Code : not available
Cutting Force : X - 4609.487561, Y - 3267.221973, Z - 5632.747960
*****
Through Hole :
Position : 100.000000, 105.000000, 0.000000
Direction : 0.000000, 1.000000, 0.000000
Diameter : 30.000000 mm Height : 210.000000 mm
Status : Machined Feature
Tooling Accessing Direction : 0.000000, 1.000000, 0.000000

```

Figure 6.4 Part of Process Plan for the Moving Bracket.

Figure 6.5 Workpiece after machining setup 1 - bottom surface F1 is milled.

Figure 6.6 Workpiece after machining setup 2 - front surface F2 is milled.

Figure 6.7 Workpiece after machining setup 3 - rear surface F3 is milled.

Figure 6.8 Workpiece after machining setup 4 - bosses F4 and F5 on side surface are milled.

Figure 6.9 Workpiece after machining setup 5 - top surface F6 is milled and features on it are machined.