Feature-based product modelling for holonic surface treatment robots

TAPIO HEIKKILÄ
VTT Automation
PO Box 13023, FIN-90571 Oulu
FINLAND

NIKOLAI D'AGOSTINO
Institute of Production Engineering and Machine Tools (IFW)
Department of Production Management
Schlosswender Strasse 5, D-30159 Hannover
GERMANY

LEILA RANNANJÄRVI
VTT Automation
PO Box 13023, FIN-90571 Oulu
FINLAND

PENTTI SALONEN
Blastman Robotics Ltd
PO Box 217, FIN-90101 Oulu
FINLAND

Abstract: In this paper we describe feature based modelling principles for specifying manufacturing data in product models. We are targeting to support robotized surface treatment application by introducing data describing the surface treatment paths (and other task attributes) into the product models. In so called holonic manufacturing systems the autonomy of the system entities is an essential feature, and by preparing the manufacturing data already into the product model we can reduce the complexity of the planning problem which the robot system has to face. We expect, that this is a necessary and adequate step to establish the autonomy for the robots. Preliminary tests to implement the feature models look very promising.

Key-Words: -feature-based product modelling, robot programming, holonic manufacturing systems, intelligent robots IMACS/IEEE CSCC'99 Proceedings, Pages:4801-4808

1 Introduction

In product development many types of design, analysis, planning and decision-making tools and software are used. Demands for concurrent engineering and for product data exchange over the enterprise borders are already reality. The role of product models to support production planning varies even in robotic applications. Robotized surface treatment tasks are typically dealing with motions over complicated shapes and surfaces, which can be determined from product models in a straight forward way. Overall efficiency and task performance can be improved by off-line programming based on utilisation of 3D-CAD models. Because of the complexity of the handled shapes a totally automatic path programming can be seen only as a goal in the far future.

In many control schemes different abstraction levels and possibilities for gradual plan development (i.e., paths and operations in off-line robot programs) are beneficial. This is also the case for so called holonic manufacturing [1], where the autonomous and cooperative building blocks of the manufacturing system, the holons, do their task by negotiation based plan creation and execution. In a holonic surface treatment robot system, the product model should support the operations in the two highest layers of the holonic surface treatment robots, considering the complete part or product (part layer), or some sub-section of it (feature layer). Within this approach the complexity of the planning and executing problem can be brought down to a manageable size.

Here we follow the feature based modelling in defining the surface treatment tasks. Features enable structured representation of the tasks, and support adding the handling knowledge in a compact way [2, 3], thus making path planning problem more feasible, and also reducing the amount of data to be communicated in negotiating the tasks between the robots. Although feature based modelling allows a higher level of automation, there is still a need for a certain amount of human integration into the planning procedures. The human designers who instantiate the surface treatment features will do it guided by the CAD system based on the dialog of the related feature model.

2 Product modelling

2.1 Geometric modelling

CAD- systems can be devided into 2D - and 3D – systems. 2D – systems represents graphical models. These are needed for handling simple or complicated curves and intended to support generation of engineering drawings and illustrations.

The geometric representation of 3D-CAD-systems can be divided into wire frame models, surface models, or solid (volume) models [2]. Wire frame models are deficient to represent 3D solid parts. Surface models mainly intended to support design and manufacture complex, sculptured surfaces. They are based on bi-parametric polynomial surface models composed on portions of surfaces, in general non-planar surface patches. Solid models can be divided into decomposition models, constructive models, and boundary models.

Boundary models can be divided into polygon, vertex, and edge based models. Polygon based boundary models consist of only planar faces, and the surface normal for the faces may be represented explicitly. Vertex based boundary models represent vertices as independent entities, and no duplicate data for a single vertex exist as in the case of polygon based models. Edge based boundary representation models include edge nodes in the data structure to represent information of curves [2]. The data structures for boundary models describe the geometric entities like vertices, edges and faces and their topological relationships.

Boundary models, or boundary representation models (B-Rep) form the basis for most of the recent 3D-CAD systems, and they are suitable also for the path planning purposes. For these reasons we shall emphasize on boundary representation models.

Current CAD systems provide many file formats for exchanging the product CAD data. Fig.1 illustrates how the development of some CAD formats has emerged from early 1980s.

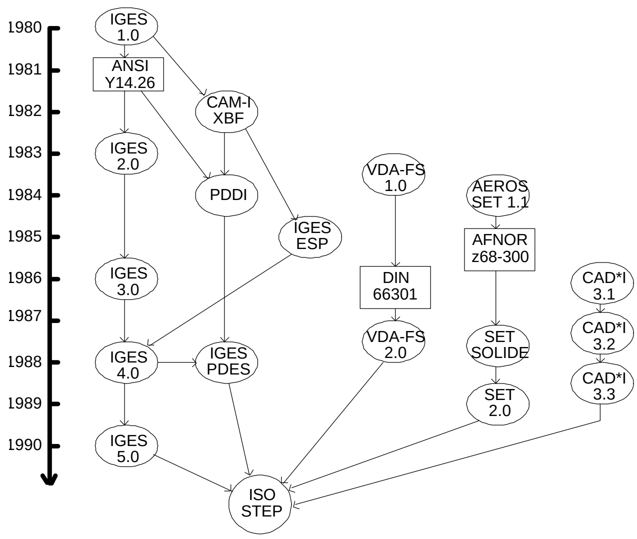

Fig. 1 Development of some major data exchange format (adapted from [4], by permission of the publisher)

2.2 Feature-based modelling

Feature based modelling provides ways to describe products from different points of view and different levels of abstraction. Features can support the creation of the product / part geometry (design features), or improve the link between the CAD models and automatic manufacturing based on e.g., NC controlled machinery (manufacturing features). Feature models are domain dependent: when a part is designed by features, the resulting model is usually not in a form convenient for other applications. Design features are stereotypical objects related to a part's function, its design intent, or the model construction methodology, whereas manufacturing features are stereotypical objects that represents specific manufacturing operation. Examples of design features include blocks, wedges, through-holes, blind holes, bases, pockets, and ribs. Examples from manufacturing features are in single part machining: bore operation, slot milling, pocket milling; in sheet metal products: hole cutting, bending and welds; and in assembly: mechanical joints as bearings. Manufacturing features consist of both geometric and manufacturing process related data e.g. path data and process parameters for surface treatment.

Generally it is also necessary to use the underlying geometric model in conjunction with the features to do the transformation of design features into manufacturing features, also called mapping. Based on the information flow connections, there are three principal ways to combine the geometric modelling system (e.g., based on boundary modelling or CSG representation) to the feature system [2]:

1. Design-by-features -> Geometric modelling system
2. Geometric modelling system -> Design-by-features
3. Design-by-features <-> Geometric modelling interface <-> Geometric modelling system

The case 3 is most flexible way, while the limitations of the modelling systems (current ‘closed architectures’ CAD software systems) may often restrict the usage into case 1. In any case, one of the primary advantages of features is that they make it possible to link design and manufacturing information in a fashion that supports use of manufacturing information during product design, and conversely design information to during manufacturing planning and actual manufacture [2].

Here we are considering features as templates to describe surface treatment paths in a way independent from the details of geometric descriptions. This means that we are dealing closest to the case 3. However, we do not create any new geometry within our manufacturing features, although update e.g., surface properties by cleaning the surfaces.

3 Feature-based product model for surface treatment tasks

3.1 Product model

Here we specify a product model data structure, which considers also the representation of manufacturing data. Basically we are relying on user defined form features, which we use as task templates carrying the path data for the surface treatment tasks. Depending on the type of feature, further decomposition into detailed path points and also with details of robot program sequence is done by the robot system. From the point of view of feature based modelling, there are two key points to remember:

- a form feature gives a compact task representation (for further calculation of detailed path points)
- different detailed operations and path patterns may be applied to same form features (reorder or add path point sequences)

The product model is consisting of geometric and manufacturing information parts. This is illustrated in Fig.2.

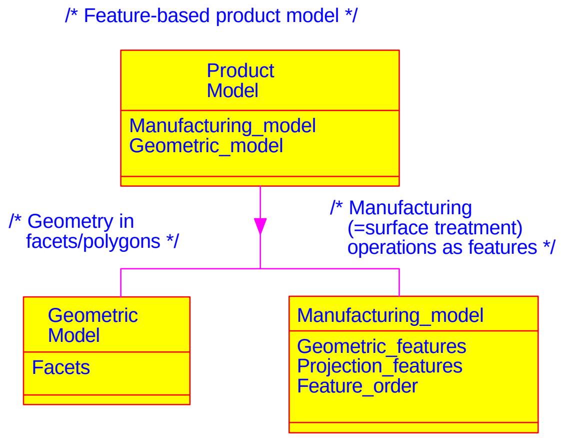

Fig.2 Product model.

3.2 Geometric model

The geometric model describes the surfaces of the solid object. It is described separately from the feature model. In principle different geometric models apply to the manufacturing features, i.e., the manufacturing features do not recognise whether they are dealing with parametric surfaces or approximated, facet based surfaces. An example of the structure of the geometric model is described roughly in Fig.3.

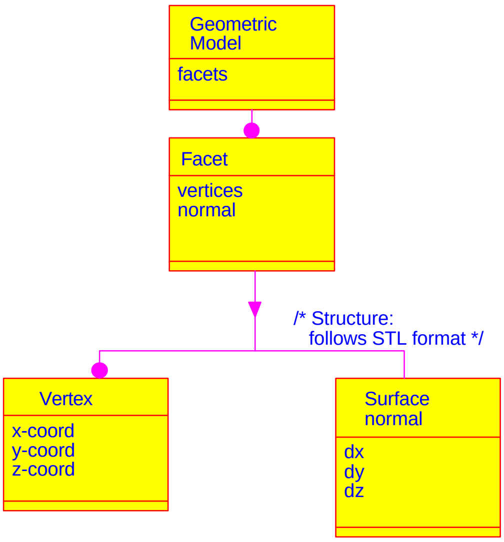

Fig.3 Geometric model.

Fig.3 illustrates the polygon based boundary model of the Stereolithography exchange format (STL), which specifies geometric models by a finite element structure based on triangular facets.

3.3 Manufacturing model

Manufacturing model gives links to the geometric and the manufacturing feature models. It also describes the highest part level task decomposition by specifying the set of features to be treated, and what is essential, sets an order for them. In more details, manufacturing features are here templates, which define constraints for a set of path points in a precise and compact way. This is profitable when the robots exchange their state and plan information within the negotiation process for allocating tasks efficiently.

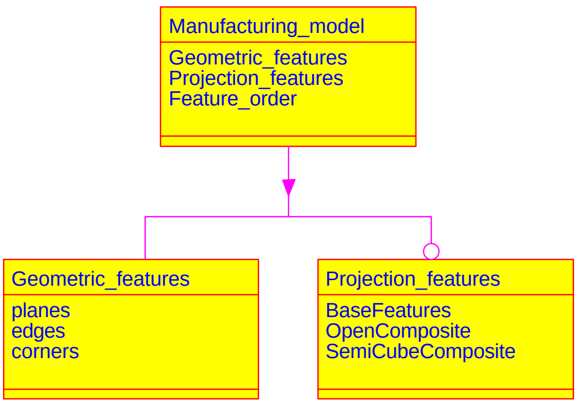

Fig.4 Manufacturing model.

The manufacturing model for robotized surface treatment gives the list of two types of features used to describe the surface treatment tasks, namely geometric manufacturing features and projection manufacturing features (Fig.4).

3.3.1 Geometric features

Geometric manufacturing features are described with characteristic points of the feature, for example, by constraining lines of a rectangular plane, and related dimensions. The points as well as the dimensions can be easily given interactively by the human operator by pointing points from the surfaces of the part, as illustrated by the geometric model. In principle, the geometric manufacturing features can also be based on elements of the geometric model, e.g., have a complete match to a surface facet. In this case the geometric manufacturing feature would be strongly linked to the geometric model and in such a way would reduce the independence between manufacturing feature model and geometric model. Here the geometric manufacturing features are divided into planes, edges and corners (Fig.5).

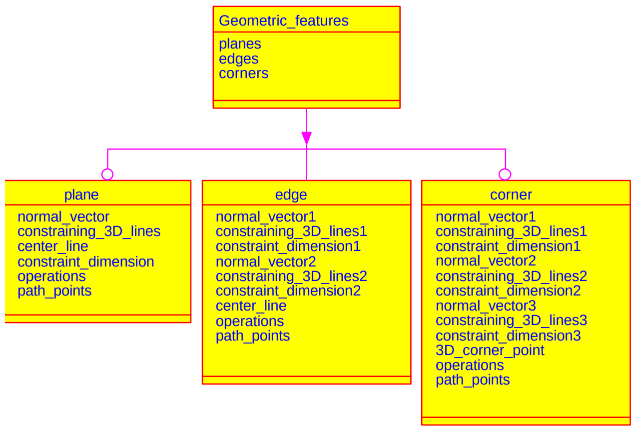

Fig.5 Geometric manufacturing features.

The plane feature is described by four corner points, and two dimensions. These specify a planar area in space in which detailed path points can easily be created and interpolated (Fig.6).

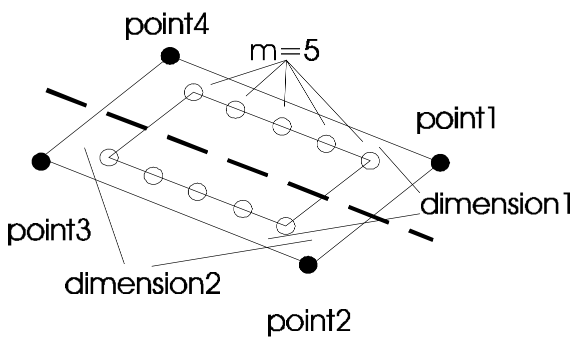

Fig.6 Plane feature.

An edge feature is very similar to a plane feature. It is specified by six characteristic points and two dimensions. These specify two planar areas in space, in which detailed path points can easily be created and interpolated (Fig.7).

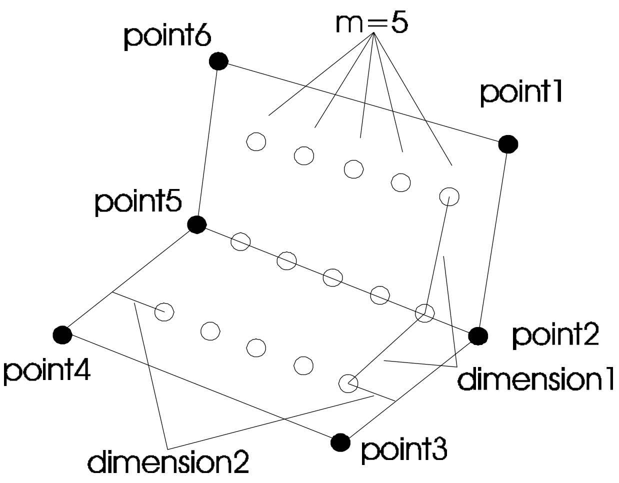

Fig.7 Edge feature.

A corner feature is very similar to the plane and edge features. It is specified by four characteristic points and three dimensions. These specify three planar areas in space, in which detailed path points can easily be created and interpolated (Fig.8).

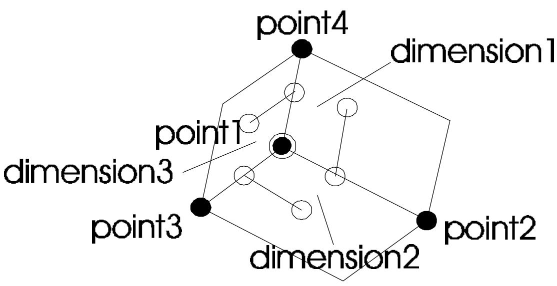

Fig.8 Corner feature.

3.3.2 Projection features

Projection features map a geometric pattern onto the object surface. A variety of ways have been defined on doing this. Basically different sets of surfaces in a given pattern are projected to the object surface, and from the resulting intersection lines the path points can be determined in certain manner. In the case of a facet based geometric model, the intersection points of the projected surface profiles and the facets of the geometric model form the basis for the path points. These can be interpolated in a desired way, either before path point generation, or even after that in the robot controller (provided that it supports this kind of interpolation, e.g., by splines).

The projection features are divided into atomic base features, or composite features which are represented with the base features (Fig.9).

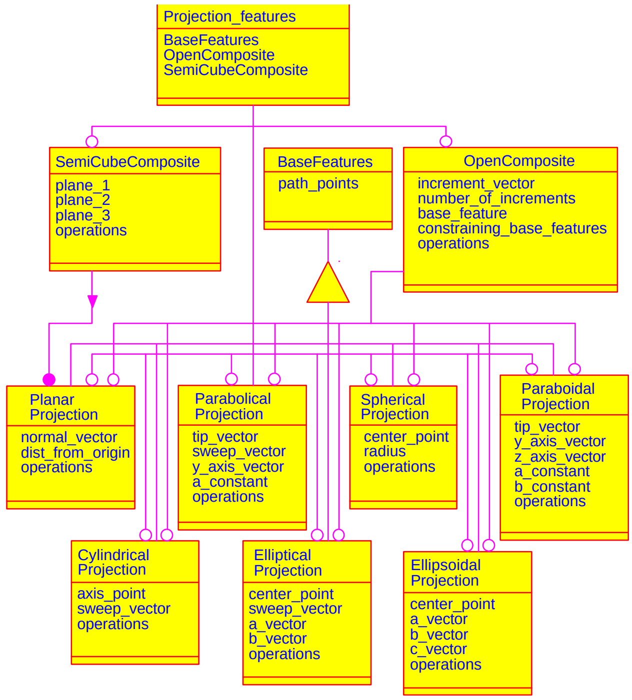

Fig.9 Projection Features.

The base features specify a geometric projection pattern, and its location in the target object co-ordinate system. The intersection profiles between the projection pattern and geometric model of the object determine the paths points. The current set of base features include the following projection types: parabolic, spherical, paraboidal, cylindrical, elliptical, and ellipsoidal.

The composite features are divided into cubic composites and open composites. Cubic composites, called semi-cube composites specify a structure similar to the geometric feature 'corner' (Fig.10). Open composites define a set of base features, for example a set of projection planes (Fig.11).

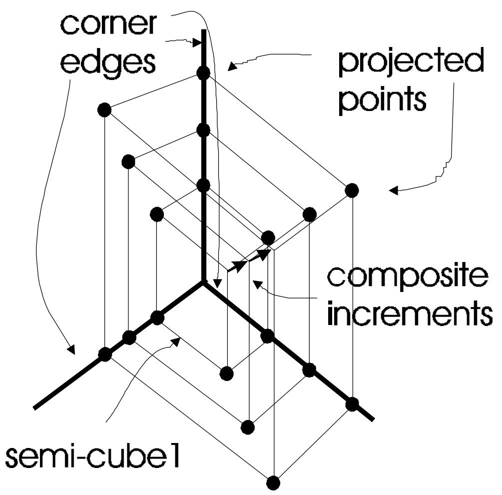

Fig.10 Cubic composite feature.

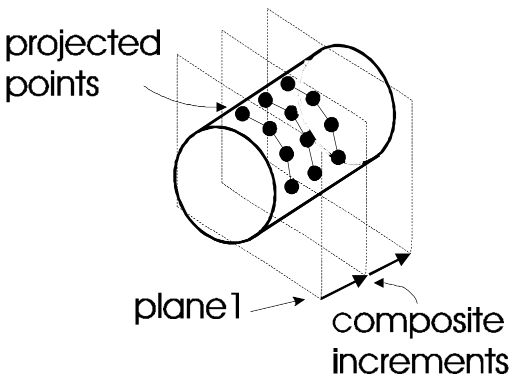

Fig.11 Composite feature 'Planes'

3.4 Comparison of manufacturing features

The surface treatment manufacturing features should make the task description easier and faster, and enable automatic task execution when several surface treatment robots are participating into the task execution. Different feature types have different characteristics, and they are best applicable depending on the shapes and complexities of the handled parts or products. A short comparison is given in the following.

- **geometric features**
  - planes, edges, surfaces
  - easily integrated to user interfaces (templates in CAD systems, human operator to instantiate these)
  - simple and fast to instantiate
  - sometimes strongly approximates the original shape
- **projection features**
  - base features by different primitive projection profiles
  - composite structures enhance the expressiveness
  - easily integrated to user interfaces (templates in CAD systems, human operator to instantiate these)
  - slower and more laborous to instantiate than geometric features
  - follows more closely the original shape

4 Examples for surface treatment manufacturing features

We made some preliminary efforts to implement the feature models. We used a prototype software designed by VTT Automation [5], and a commercial CAD system, the Pro/Engineer, version 19 [6]. The goal was to create examples of user defined features for projection and geometric features as specified above. The ultimate goal was to be able to instantiate shot blasting features by first selecting the feature type to instantiate, and then giving feature data by "clicking" the characteristic points of features on the screen. The CAD system should have guided the instantiation process by command lines, dialogue boxes etc.

4.1 VTT's software

In VTT's software the geometric model is based on the STL representation, i.e., based on solid objects with triangular faceted surfaces. In more details, it is polygon based boundary model, and specifies the geometric models by a finite element structure based on triangular facets (Fig.11). STL files can be either in ASCII or binary form and here we are using the ASCII form.

```
solid
. . .
  facet normal 0.00  0.00  1.00
    outer loop
      vertex    2.00  2.00  0.00
      vertex   -1.00  1.00  0.00
      vertex    0.00 -1.00  0.00
    endloop
  endfacet
. . .
endsolid
```

Fig.11 Triangular facet from a solid object in STL format.

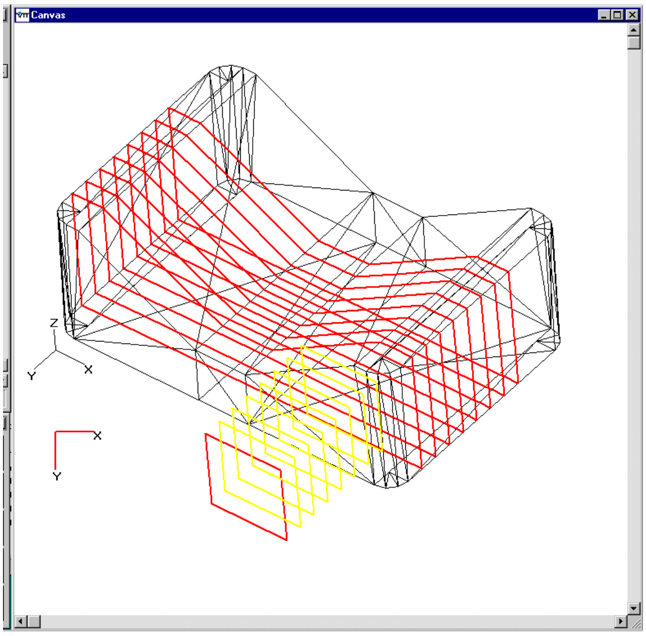

Fig.12 Example of a user defined feature in VTT software.

We implemented the 'plane' projection feature, and further on 'open composite' feature using the 'plane' projection features (Fig.12). With the current system the user can create the multiple projection patterns and locate it related to the target object, and create path points based on projection profiles. In addition, some feature related manufacturing parameters can be stored in the feature data structure. The feature data is stored and accessible by the robot system via an ASCII formatted interface file.

4.2 Pro/Engineer application

4.2.1 General description

The commercial 3D-CAD-System Pro/ENGINEER uses a feature-based approach for geometric modelling. For the internal geometry representation a B-Rep geometry kernel is used. Pro/ENGINEER offers a library of several geometric design features that are devided into special classes of features (Table 1).

Through the comprehensive application programming interface (API) of Pro/ENGINEER it is possible to extent the functionality and the user interface.

Solid class	Surface class	Datum class
Protrusion	Flat surface	Plane
Hole	Offset surface	Curve
Slot	...	Point
...		...

Table 1. Some feature types in Pro/ENGINEER

4.2.2 User defined features

Pro/ENGINEER allows the definition of user defined features (UDF). A UDF is a composition of built-in features. For the definition of the UDF the user has to model it by using the built-in features Pro/ENGINEER. After modelling, the defined features can be combined to one UDF. Therefore the dialog queries for the positioning references in order to allow an automated rebuilt of a new instance. A UDF represents a template of a specific feature combination that can be changed afterwards by modifying the feature parameters.

4.2.3 Implementing the EDGE feature as a UDF

For the definition of an EDGE – feature (Fig.7) the 6 characteristic points has to be defined. Therefor the Pro/ENGINEER datum class feature *Point* is used. The positioning references have to be defined. There are several possibilities in Pro/ENGINEER to position a point. Examples of positionings are “On Surface”, “Offset from surface”, “Curve intersection” and so on. Every positioning stays associative.

After point creation, two surface class features are defined using the charachteristic points as surface corners. The system ensures complete associativety between face corners and points. This allow consistent geometry changes of instantiated UDFs. After definition, the datum points and the flat surfaces are combined to an UDF by defining the positing references. The UDF can be saved in the UDF-library using the name EDGE. In order to reduce the amount of requested user input, relations can be defined. Relations drive dependencies via expressions that use feature parameters. This allows an automated update of the dependent feature parameters.

To instantiate the UDF “EDGE” it has to be chosen from the UDF Library. After that, the positioning references are queried by the system. These references are two surfaces on the part that are to be surface treated and three reference edges that are used for the point positioning references.

After instantiation of the EDGE feature the feature parameters, that drive the point positions can be modified. The system saves the original values that are used during UDF definition. During the instantiation, a short window showed the shape of the original EDGE feature (Fig.13). This allows the correct identification of the reference elements.

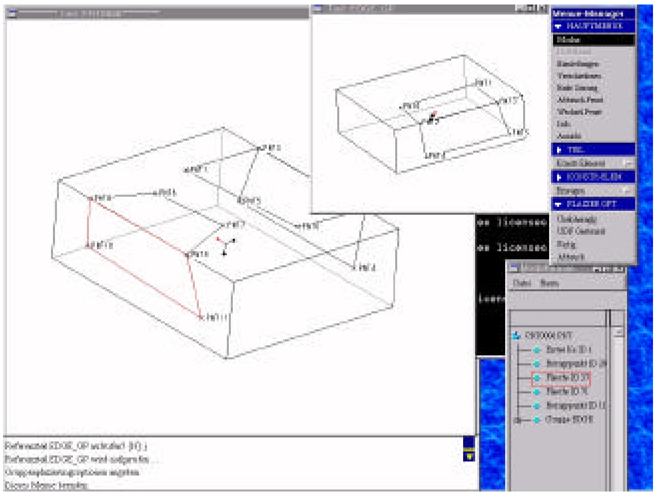

Fig. 13 Example of a user defined feature in Pro/Engineer.

4.2.4 Future extensions

With the API of Pro/ENGINEER, it is possible to improve the user interface, in order to simplify the instantiation process, especially positioning. In addition, the API allows access to both the feature layer and the geometry layer of the 3D-CAD-Model. This allows us to automatically calculate the detailed path points on the EDGE feature after the UDF instantiation. Pro/ENGINEER is also supporting some parts of the ISO10303 STEP standard [7, 8] and that can provide a general exchange format in building the link between the CAD and robot systems. These will be actions to be done in the next steps of the development.

5 Conclusion

In this paper we have described feature based modelling principles for specifying manufacturing data in product models. More specific, we are targeting to support robotized surface treatment application by introducing path data into the product models. In so called holonic manufacturing systems the autonomy of the system entities is an essential feature, and by preparing the manufacturing data already into the product model we can reduce the complexity of the planning problem which the robot system has to face and we expect, that this is a necessary and adequate step to establish the autonomy for the robots. We do all this by specifying user defined features, which should be easily implemented in the commercial CAD systems. Preliminary tests to create the feature models in our own system and in a commercial CAD system look very promising.

References:

[1] Rannanjärvi L., Heikkilä T., Software Development for Holonic Manufacturing Systems. *Computers in Industry* Vol 37, 1998. Pp. 223 - 253.

[2] Shah J.J, Mäntylä M., *Parametric and Feature Based CAD/CAM*. John Wiley & Sons, New York, 1995. 619 p.

[3] Grabowski H., Anderi R., Pratt M.J. (eds), *Advanced Modelling for CAD/CAM Systems. ESPRIT Research Reports, Project 322, CAD Interfaces (CAD*I).* Springer-Verlag, Darmstadt, Germany 1991. 113 p.

[4] Al-Hazmi K., STEP & EXPRESS Language. DAKE Centre, University of Keele, Research report DAKE/TR-94007, October 1994, 47 p.

[5] Heikkilä T., Gironella-Ferrer L., and Annala M., Model Based Interactive Path Planning for Surface Following Robot Tasks. Proceedings of SPIE, vol. 3208. Intelligent robots and computer vision XVI: Algorithms, Techniques, Active Vision, and Materials Handling, 15 – 17 October 1997, Pittsburgh, USA. Pp. 551 - 560.

[6] The Pro/ENGINEER Solutions Advantage - A Brief Product Overview. Parametric Technologies Corporation, Waltham, USA http://www.ptc.com/products/proe/overview/index.htm

[7] Next STEP in Intelligent Data Exchage. *Data Engineering*, February 1996, pp. 27 - 30.

[8] Gu P., Norrie D. H., *Intelligent Manufacturing planning*. Chapman & Hall, London 1995. 342 p.

ACKNOWLEDGEMENTS

This work has been part of the contributions of VTT Automation, University of Hannover/IFW, and Blastman Robotics Ltd in the project "Holonic Manufacturing Systems" (BRPR-CT97-9000), belonging to the international IMS programme (Intelligent Manufacturing Systems). The work has been supported by the European Commission, which is greatly acknowledged by the authors.