PERIODICA POLYTECHNICA SER. MECH. ENG. VOL. 50, NO. 2, PP. 99–113 (2006)

NON-CLASSICAL REVERSE ENGINEERING CONCEPT BASED ON MACHINING FEATURE RECOGNITION

Attila FRIEDRICH and Gyula MÁTYÁSI

Department of Manufacturing
Budapest University of Technology and Economics
H–1111 Budapest, XI. Egry József Str. 1. E. II. 11., Hungary

Received: June 14, 2006

Abstract

This paper is focusing on the fact that technological reconstruction is more important than the obligate geometrical reconstruction. We refer in our study to cases of reconstruction of simple mechanical parts with mainly analytical surfaces. This is because technological reconstruction can provide us with the most important information for/about CAPP (Computer-Aided Process Planning). This information is very helpful in the tasks of a designer in operation planning and also in an operation pass planning level.

Keywords: reverse engineering, feature recognition, feature technology.

1. Introduction

There are several methods and applications for the reconstruction of a real physical object. These methods generally support the representation of different artificial objects (e.g. artificial parts archaeologies etc.) in geometrical form. Other scopes of these concepts are the full-reconstruction of special free-form mechanical objects. The main reasons for using these concepts are to provide information for different CAD systems. These systems could analyse the information by special analysing processes (for instance: wind-channel analysing, forming optimal electromagnetic areas etc). Based on the reconstructed object by using the previous concepts the planning of the complex production processes can be very simple. The reverse engineering philosophy plays a very important role in the production of spare parts where the designing and manufacturing documentation is not available.

This paper is focusing on real physical objects which contain mainly analytical surfaces. This new method combines procedures of digital image processing and the CSG design concept. The result of this new method will be a parametrical technology model with a clear structure. Based on the previous description, this new method got the name: VA-REFAB which means Vision-Aided Reverse Engineering FeAture Based.

Fig. 1 illustrates the general difference between the so-called classical reverse engineering (the above mentioned first method) and the VA-REFAB concept.

As a first step towards addressing this difficulty, we have developed a formulization of the problem of recognizing a subset of the set of all machinable fea-

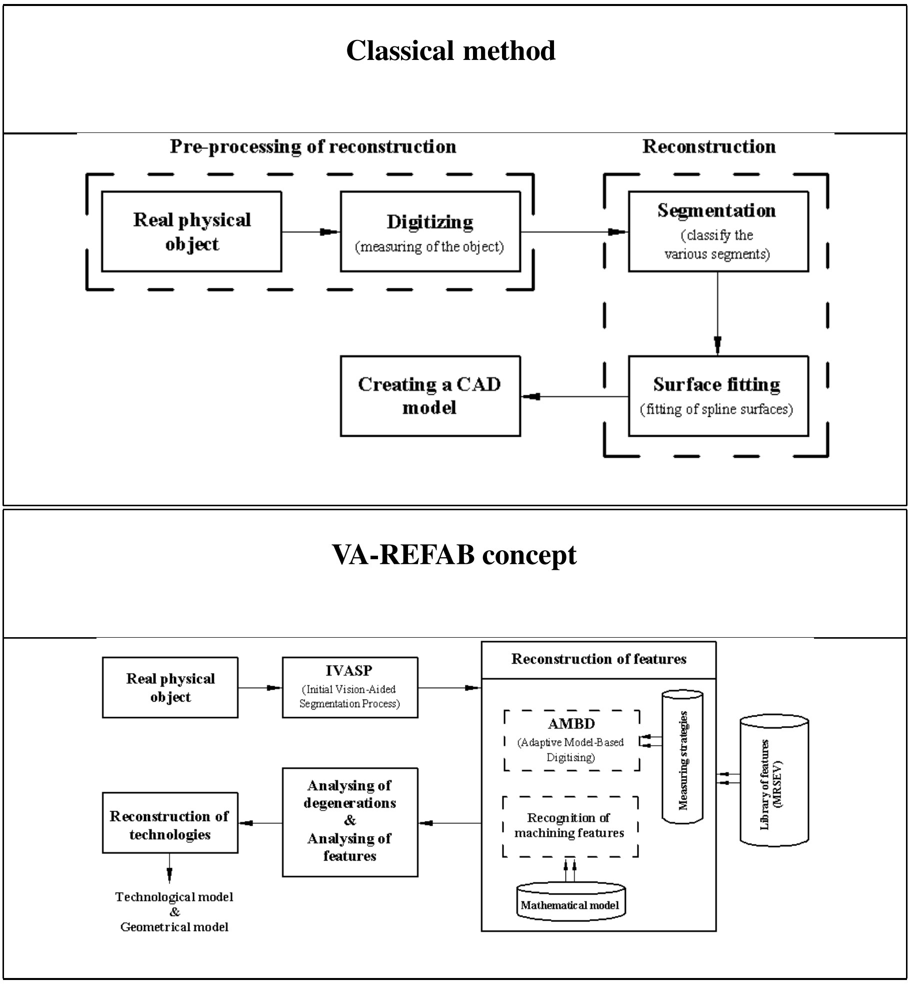


Fig. 1. Flow-chart of a classical reverse engineering method and the VA-REFAB concept

tures expressible as MRSEVs (Material Removal Shape Element Volumes) developed by Thomas Kramer at NIST. MRSEVs are volumetric features corresponding to machining operations on 3-axis milling machines. Based on this formulization, we have developed an algorithm for solving the problem of recognizing every solid that can be described as the difference between an arbitrary piece of stock and an arbitrary set of machinable features. Currently, our approach is designed only to handle linearly swept features (i.e. holes and pockets). However, our definitions of holes and pockets are more general than the definitions used in a number of feature recognition systems; for example, the pockets may be complicated swept contours that include corner radii and islands.

2. Related Work

Developments in feature recognition have been closely tied to advances in solid and geometric modelling. Many early feature recognition efforts focused on domains of polyhedral parts, convex feature primitives, and algorithms to find patterns in graphical boundary representation data structures. As solid modelling technology has advanced, increasingly realistic and complex real world parts can be modelled. The advance in solid modelling representations, however, has not produced a corresponding advance in feature recognition technology to handle the more realistic parts. Feature recognition techniques are often based on assumptions about polyhedral objects.

There have been many efforts to classify the hierarchy of machining features. Two of the most mathematically comprehensive approaches for defining machining features are those of CHANG [2] and VANDENBRANDE-REQUICHA [7]. Chang's feature definitions are based on the shape of the cutter tool and the cutting trajectories. Requicha similarly classified volumetric machining features in terms of swept volumes.

A very important contribution of TRIKA and KASHYAP [6] is related to the issue of completeness. The input of feature recognizers is typically a solid model for the desired part, and a solid model of the stock (raw material). The material to be removed by machining, called delta volume is computed by subtracting the part from the stock. Trika and Kashyap called the feature recognizer complete if, for every part, the delta volume is contained in the union of all volumetric features generated by the feature recognizer.

The work of HENDERSON [1] was influential in employing expert systems on the feature recognition problem. Perhaps the most formal approach to date has been attempted by VANDENBRANDE [7]. This method provides a computationally rigorous way of recognizing a class of realistic machining features via artificial intelligence techniques in combination with queries to a solid modeller.

KRAMER [3, 4, 5] has developed a STEP-based feature library of Material Removal Shape Element Volumes (MRSEVs). This defines a hierarchy of volumetric machining feature classes, each characterized in terms of required and optional attributes. By using the EXPRESS modelling language, MRSEVs define 48 STEP form features. MRSEV instances have been used for applications such as process planning and NC-program generation. Kramer's MRSEV types include linear swept features, edge-cut features, ramps and rotational pockets. The subtypes of the primary MRSEV volume and their approximate shapes are as follows. In most cases there are further restrictions on the shapes so that the shapes can be produced by machining. Each shape is bounded on one side by a plane which forms the upper surface of the MRSEV volume and lies perpendicular to the axis of the cutting tool when the shape is in position to be machined.

While automated machining feature recognition has emerged as critical technology, many approaches that have been developed lack a consistent formulization of the problem, thus their overall utility has been difficult to evaluate. Further, many approaches employ techniques that are inherently limiting; either representationally or in terms of the computational complexity of the reasoning and recognition algorithms. Few approaches have demonstrated the ability to scale to real world artifacts and even fewer have presented concise mathematical means with which to specify the domain of features, alternatives, and parts that they are capable to handle.

3. Geometrical or Technological Reconstruction?

The before mentioned methods assume the existence of a geometrical model from a real object and to extract the various machining feature representation. In our case we can start only from the real physical object and nothing besides, so the task to trace the different features is very complicated. Tracing to define the set of features, the classical methods use a measured point set based on a digitizing process. The VA-REFAB employs image processing algorithms as mentioned before (see *Fig. 1*). The MRSEVs by Kramer underlie the machining feature recognizing of an unknown real object using the VA-REFAB concept.

The feature concept had its beginning with the process planning of machined parts. Historically, process planning systems for machining have employed features to represent machining operations. Machining features have grown to fill important roles in a variety of manufacturing application domains, such as assembly, inspection, etc.

A number of attempts have been made to define and classify machining features. Although there are differences among these approaches, many of them share important similarities. For example, a machining feature usually corresponds to the volume of material that can be removed by a machining operation. A machining feature attempts to capture the effect of a cutting tool (such as a drill or a mill) used in a machining center to operate on a workpiece. In general, machining features model material removal operations. For example, a machining feature might be defined as the volume swept by a cutting tool during machining and can be represented as a parameterized solid.

Before the beginning of the reconstruction of an unknown physical object based on a measured point set, it is important to define the goal of the reconstruction, which could be the following:

1. If the goal of the reconstruction is a simple presentation of an object (e.g.: artificial parts or archaeologies), then the accuracy and the structure of the model is not so important. That means that the classical fast-reconstruction concept is acceptable.
2. In the case of mechanical parts with only freeform surfaces, the goal should be to prepare as an accurate CAD model as possible. The product will only be acceptable if the geometrical model-representation is the best approach of the real object. In this case the classical method provides the best results like

before, because the classical method works only with different parametric spline surfaces (Bezier-spline, B-spline, rational B-spline, etc.).

3. In the case of an unknown object - like a simple mechanical part - which contains mainly analytical surfaces, the VA-REFAB concept will provide the best solution. In this case the goal is not only a model-representation of an unknown object, but also to create a technology model too. This technology model directly supports the CAPP, which has a positive effect on the required time of the process planning.

Using the VA-REFAB concept, this paper presents a possible solution for the reconstruction of a simple mechanical part, and presents the reconstruction of a full object based on machining feature primitives to support the process of manufacturing and the production planning.

So the main goal is to define reconstruction by technology feature-primitives as quickly and as accurately as possible which are identical to the manufacturing allowances. The final result of the VA-REFAB concept is also a model (geometry and technology) like before, however this model is a structured and parametrical model using a special interface – called COM interface of a CAD system. The benefits of this model are the clear structure and the robust support for the pre-processing of the manufacturing phase.

4. Machining Feature Extraction by VA-REFAB

Just as there may be many different possible ways to achieve a goal state in AI planning, in manufacturing there usually exist several different ways in which a design can be realized. If features are in one-to-one correspondence with manufacturing operations, then there may be many different alternative sets of features that transform an initial workpiece into a final part. Early work on feature recognition focused on finding single best feature decomposition for a given part.

The final result of a classical reconstruction is mostly a simple geometrical representation of an unknown physical object. Studying the related works the conclusion is that these models and methods do not give any directives to CAPP and to the other technology like this. Although the reconstructed models are coherent geometrical representations of the physical objects, there is no guarantee that the structure of this model is exact and correct according to the point of view of the technology and manufacturing process.

In case of classical reconstruction the surface segments described by a measured set of points are approaching the original object with implicit surfaces very well; but the final model does not include the features of these surface segments. For instance in case of a simple hole where the type of the segment could be detected based on a digitized point set, and could be described as a cylinder surface in implicit form (an equation could be definable). So in this process a lot of important information remained unused, like in the previous case which was a special hole feature with some descriptive characteristics.

a.) ***P*** Part b.) ***P*** Part and ***S*** stock

Fig. 2. An example of part and correspondent stock

The reconstruction based on machining features is a method of reverse engineering with a new concept. The main part of the CAD systems used in practice works with different features based on so-called CSG (Constructive Solid Geometry). The background of this philosophy is the different boolean operations. A possible system of the machining features was worked out by Kramer. This is the well-know MRSEV (Material Removal Shape Element Volumes), which determines the primitives and the feature classes with the help of the set of attributes.

Functionally the machining features could be identified as allowance forms. The VA-REFAB concentrates on the material-removal technology as milling or drilling. Based on this only one boolean operation could take into consideration which is the subtraction (**-***).

Throughout this paper, we let ***P*** be a solid representing a part, and let **S** be a solid representing a stock from which ***P*** is to be made. The delta volume is the solid

$$\Delta = \boldsymbol{S} \;\textbf{-*}\; \boldsymbol{P}.$$

One of the main benefits of the partitioning based on machining features is that it clearly specifies the set of usable technology, additionally robustfully and quickly supports to determine the trajectories of the NC production. *Fig. 2* illustrates such cases where using the feature attributes the moving trajectories are directly determinable. This partitioning plays very important role in choosing the cutting tools (type of tool, dimensions of tool). That means it is not definitely necessary to create a geometrical/CAD model of the object, but only the technological representation of the allowance shapes is necessary. These representations are machining features in the VA-REFAB concept. Another benefit of the VA-REFAB concept is that the different segments of the object (or model) could be easily described by simple parameters which well support the latter modifications. *Fig. 2* shows an example of part and stock. Throughout this paper, this example will be using to illustrate various steps in our approach.

The VA-REFAB employs a new method for the recognition of various features. This is the image processing sequence, which plays very important role in terms of time and accuracy of the measuring process because in contrast to above mentioned classical methods the VA-REFAB concept supports to plan the measuring sequences. To state the different segments of the object we use the detected characteristic curves on the range image, which curves designate the boundaries of the homogeneous surfaces of the object. Using these curves the planning of the measuring process is easier.

We dissociate the measuring sequence into two different types. At first we have to measure the bottom surface of the features, which specify the orientation of the features. The other one is the measuring of the characteristic curves (profile curves). To communicate with the measuring machine (CMM) we define the measuring program in DMIS interface format.

```
[PartProgram]
N1=ANGUNITS/ANGDEC180
N2=GOTO / ABS, CART, 42.2500, 0.0000, 50.0000
N3=S(S2)=SNSDEF/PROBE,INDEX, 0.00, 0.00, 0.00,90.00,180.00, 0.00, 0.500
N4=SNSLCT/ S(S2)
N5=GOTO / ABS, CART, 42.2500, 0.0000, 50.0000
N6=GOTO / ABS, CART, 42.2500, 0.0000, -6.0000
N7=GOTO / ABS, CART, 42.2274, -1.3811, -6.0000
N8=$$ BEGIN_PROFILE_LEFT
N9=CPOINT/MEAS,"PROFILE_LEFT_TOOTH_1",NUMBER= 1
N10=PTMEAS/CART, 30.73356565, -1.00520766, -6.00000000,ANGDEC180,
91.87331444, 178.12668556, 90.00000000
N11=ENDMES
N12=CPOINT/MEAS,"PROFILE_LEFT_TOOTH_1",NUMBER= 1
N13=PTMEAS/CART, 30.82394285, -1.00816364, -6.00000000,ANGDEC180,
91.87331444, 178.12668556, 90.00000000
N14=ENDMES
.
.
.
```

Fig. 3. The created measuring program in DMIS interface format

The common problem of this sequence is to define correctly the plane of the measuring process. This problem is addressable based on the assumption that the plane of the measuring is equivalent with the image plane. *Fig. 4* shows how to define the measuring plane based on image plane.

Based on the results of the image processing and the measuring sequence the various features could be created. For example, one possibility is that the characteristic curves are coplanar with the boundary of the bottom surface of the end-milling feature, such as shown in *Fig. 5 (b,c,d)*. Another possibility is that the bottom surface of the drilling-feature (through hole) has been eliminated, as illustrated in *Fig. 5 (a)*.

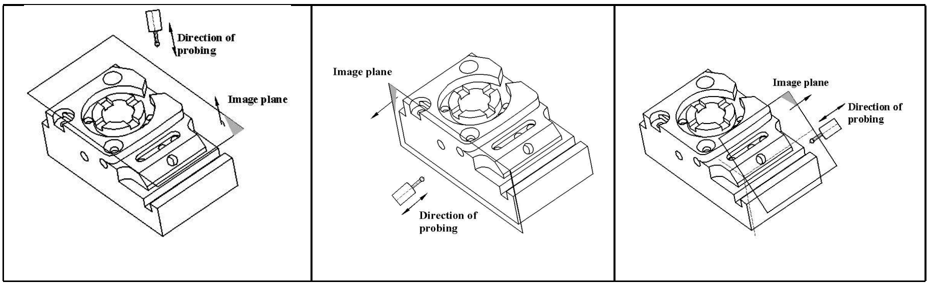


Fig. 4. Compute the probing direction based on the orientation of range image

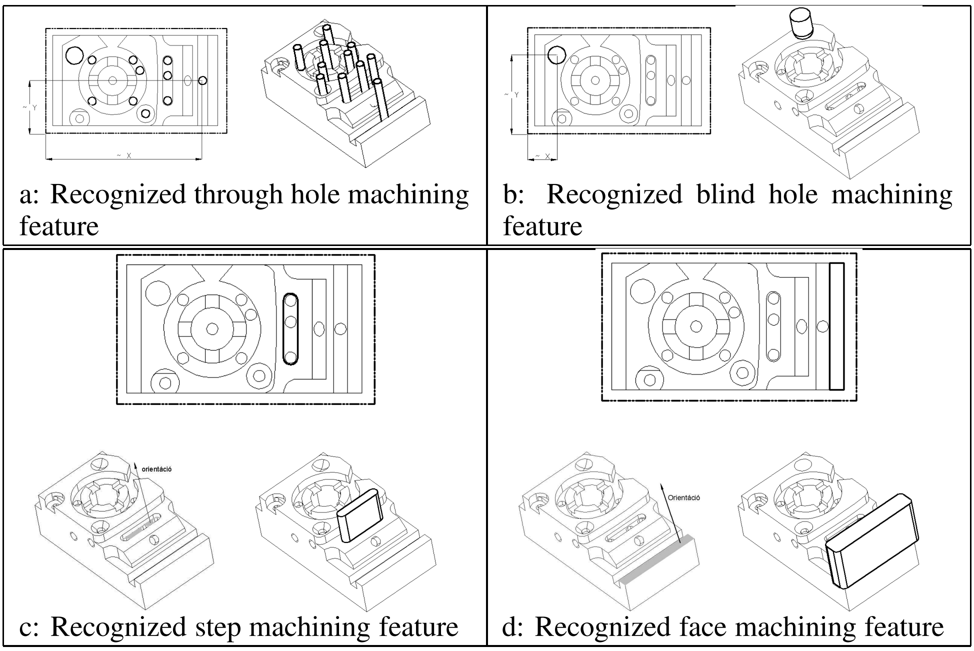


Fig. 5. Recognized various machining features based on characteristic curves on range image

5. Case Study

The previous chapters illustrated the sharp differences between the classical reverse engineering methods and the VA-REFAB concept. But it is very important to emphasize that the two different methods aim at the fast and correct reconstruction of different types of the unknown objects.

The different classes of these objects could be definable as follows: if the object contains mainly freeform surfaces then the classical methods could be the best choice. If the object contains simple mechanical parts with analytical surfaces (plane, cylinder, sphere, cone) then the VA-REFAB provides the faster and more robust solution. Because of this, a fair and correct comparison procedure does not exist.

So the goal of this chapter is not the comparison, but just to show the over-balance benefits of VA-REFAB. The emphasis will be put on the structure and the modifiability of the generated model.

5.1. Classical Method for Geometrical Reconstruction

For illustrating the classical method, let us see the different steps of the reconstruction in the case of a simple object represented in *Fig. 6*.

Based on the above example and examining the defined CAD model, it is conspicuous that where the surfaces join the edges on the real object, there the model defines a smooth surface (see *Fig. 6*). Here we have to mention, that in the reconstruction application, the default parameters and optimized parameters by external system were used.

So the explanation is that there are no measured points on the boundary of the different segments of the surfaces, so the approach has a large deviation. The further or rarer the points of point set on the range of boundaries, the higher inaccuracy of the reconstruction will be the result.

5.2. VA-REFAB concept

The situation could be far better, if the different sub-surfaces would be available separately in a given predefined structure. This structure is identical with the model history in the CAD systems, which describes the order of the features. In the case of VA-REFAB the model history is the graph mapping of machining features. *Fig. 7* shows the steps of the reconstruction using VA-REFAB concept.

The differences are apparent between the classical and VA-REFAB reconstruction procedures. The created model is much more realistic when using the VA-REFAB concept. Additionally the VA-REFAB method supports the quick and efficient modifying of the model. The defined model directly supports the CAPP giving the different feature primitives by choosing the cutter tools and giving the direct determinable cutting trajectories.

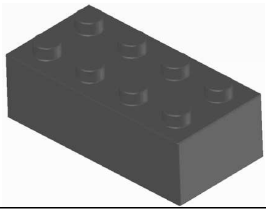
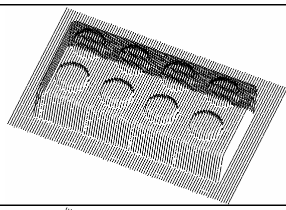
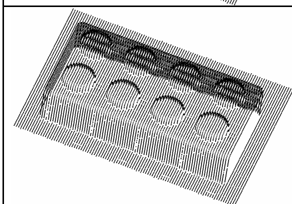
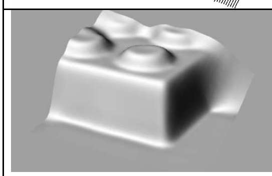
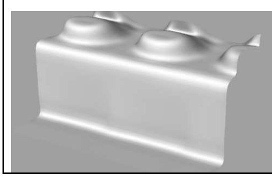
	**INPUT**: The digitized set of unorganized points
Digitizing with touch-probe *Set of points = 20419 pc* *Digitizing time= 158 min*	
After filtering and segmentation *Set of points = 20109 pc*	
Surface fitting *Imageware 10.5* *Rhinoceros 3.0* Format: IGES	 

Fig. 6. The steps of a classical reconstruction process

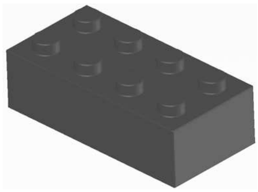
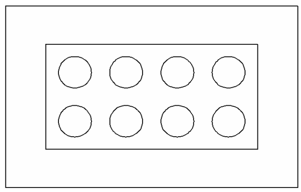
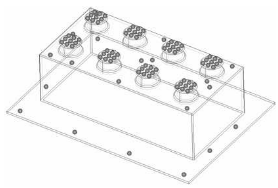
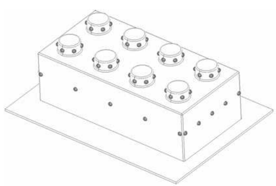
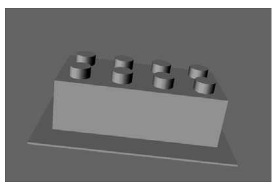
	
INPUT: Detected characteristic curves on the range image using the Initial Vision-Aided Image Segmentation Process (see Fig.1.)	
Measuring with touch-probe (bottom surfaces) *set of points n = 133 pc* *Measuring time t = 8 min*	
Measuring with touch-probe (side surfaces) *set of points n = 56 pc* *Measuring time t = 6 min*	
Creating the CAD model through OLE interface *(SolidWorks)* Format: native	

Fig. 7. Result of the reconstruction based on machining features

6. Results

The examples below are the output of VA-REFAB. The orientation of the milling feature is noted by their extensions beyond the ***S*** stock material.

Fig. 2 illustrates the different machining features as results of a reconstruction process. Direct using of these reconstructed feature-primitives could determine the technology attributes (e.g.: the dimensions of the cutter tools, the cutting parameters, the manufacturing trajectories, etc.) The VA-REFAB concept defines the model shown in *Fig. 7* based on the intermediate information shown in *Fig. 8*.

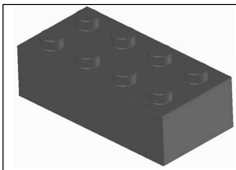
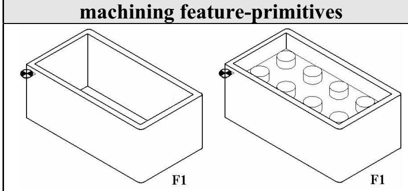
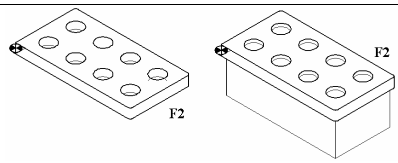
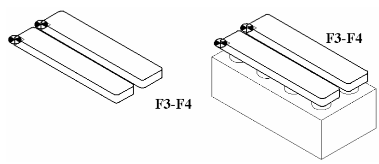
	**Reconstruction with machining feature-primitives**	**Calculated attributes of technology**
		Feature: step Technology: milling Tool: end-mill cutter D = 8 mm L_{min}=27 mm
		Feature: open slot Technology: milling Tool: end-mill cutter D = 10 mm L_{min}=5 mm
		Feature: face milling Technology: milling Tool: end-mill cutter D = 12 mm L_{min}=8 mm

Fig. 8. The features identified by VA-REFAB with calculated machining START position for a LEGO piece

Fig. 8 shows an example of a simple part with 3 various reconstructed features.

Based on the recognized machining features, two main things can be determined. Firstly the machining technology, and secondly the main parameters of this machining technology. This is very helpful in all levels of the CAPP (computer-aided process planning).

Fig. 9 presents a part with 39 planar, cylindrical and spherical faces to be machined out of a rectangular block of stock material. The VA-REFAB identified 16 drilling features and 23 milling features. The computed attributes of the technology have been emphasized in *Fig. 9*.

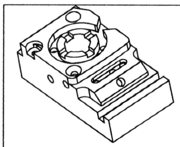
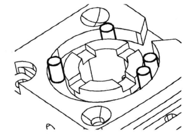
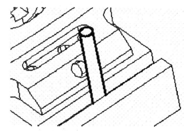
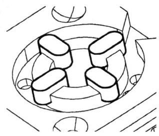
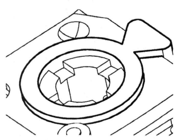
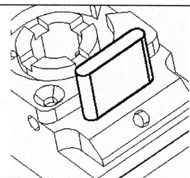
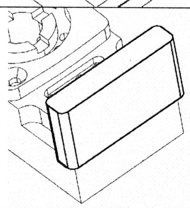
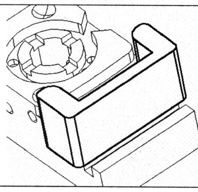
	**Reconstruction with machining feature-primitives**	**Calculated attributes of technology**
		Feature: blind hole Technology: drilling Tool: drill D = ∅ 8 mm L_{min} =17 mm
		Feature: through hole Technology: drilling Tool: drill D = ∅ 8 mm L_{min} =68 mm
		Feature: step (open slot) Technology: milling Tool: end-mill cutter D = ∅ 10 mm L_{min} =5 mm
		Feature: step (open slot) Technology: milling Tool: end-mill cutter D = ∅ 10 mm L_{min} =12 mm
		Feature: pocket (closed slot) Technology: milling Tool: end-mill cutter D = ∅ 10 mm L_{min} =15 mm
		Feature: face Technology: milling Tool: end-mill cutter D = ∅ 12 mm L_{min} =35 mm
		Feature: step Technology: milling Tool: end-mill cutter D = ∅ 10 mm L_{min} =35 mm

Fig. 9. A part with the recognized machining features

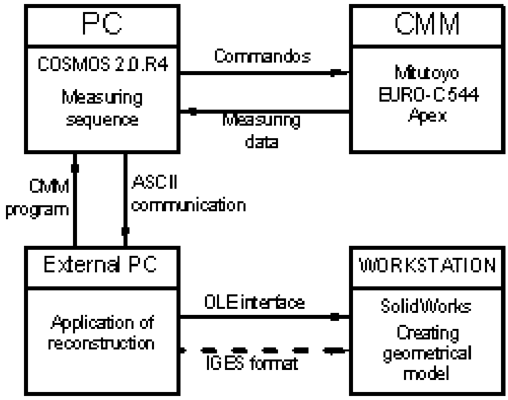


Fig. 10. Configuration of the system components for the implementation

7. Implementation

In order to prove the effectiveness and feasibility of the proposed method, the pre-processing of data points is necessary for the geometric model which have been created. A Mitutoyo EURO-C Apex 574 co-ordinate-measuring machine equipped with a Renishaw PH10M touch probe and COSMOS measurement software was used. To ensure that the proposed method is useful for practical application, a commercial CAD system (*SolidWorks*), was integrated in the implementation. The system can identify the parts shapes and further extract some identical or different categories of the feature face to be measured.

We have built an implementation of this machining feature recognition methodology in Delphi version 5. The current implementation of the feature recognizer omits bottom blends on pockets as they are not crucial to the application. Implementation for general through pocket is restricted by the current version of the PARASOLID application procedural interface.

8. Conclusion

We have described our approach for recognition of machining features from a range image about an unknown physical object. The algorithms we present take a CAD model and extract all instances of MRSEV features. Some of the primary characteristics of our approach are as follows:

1. While various CAD and CAM applications may have compatible goals and functionality, their specific details are different enough that integration has

proven difficult. To address this, our approach recognizes features from the MRSEV library describing general machining operations on 3 axis machining centers. In addition to feature recognition, these algorithms can be viewed as means of transfer from a solid model to a STEP representation.

2. Our approach handles a variety of hole and pocket MRSEVs. When possible, the MRSEV features reconstruction gives information about the dimensions of the cutting tool to be used for machining. The new offset features correspond more naturally to the area which will be machined to produce the desired removal volume.

References

[1] BEDWORTH D. D. - HENDERSON, M. R. – WOLFE, P.M., Computer-Integrated Design and Manufacturing. McGraw-Hill, (1991.)

[2] CHANG, T.-CH., *Expert Process Planning for Manufacturing.* Addison-Wesley Publishing Co., Reading, Massachusetts, (1990)

[3] KRAMER, T. R., A Library of Material Removal Shape Element Volumes (MRSEVs). *Technical Report NISTIR 4809, The National Institute of Standards and Technology, Gaithersburg*, (1992).

[4] KRAMER, T. R., Issues Regarding Material Removal Shape Element Volumes (MRSEVs), *The National Institute of Standards and Technology, Gaithersburg*, MD 20899, March 1992.

[5] KRAMER, M. R., An Express Schema for Machining Plugged into ALPS4; *Institute of Standards and Technology, Gaithersburg, MD 20899, January 1991.*

[6] TRIKA, S. N. – KASHYAP R. L., Geometric Reasoning for Extraction of Manufacturing Features in Iso-Oriented Polyhedrons. *IEEE Trans. Pattern Analysis and Machine Intelligence*, (1994).

[7] VANDENBRANDE, J. H. – REQUICHA, A. A. G., Spatial Reasoning for the Automatic Recognition of Machinable Features in Solid Models. *IEEE Trans. on Pattern Analysis and Machine Intelligence*, pp. 1269–1285, December 1993.