

Building MRSEV models for CAM applications

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In integrating CAD and CAM applications, one major problem is how to interpret CAD information in a manner that makes sense for CAM. The goal is to develop a general approach that can be used with a variety of CAD and CAM applications for the manufacture of machined parts.

In particular, a methodology is presented for taking a CAD model, extracting alternative interpretations of the model as collections of MRSEVs (material removal shape element volumes, a STEP-based library of machining features), and evaluating these interpretations to determine which one is optimal. The evaluation criteria may be defined by the user, in order to select the best interpretation for the particular application at hand.

Key words: design critiquing, CAD/CAM integration, feature recognition.

1 INTRODUCTION

Although various CAD and CAM applications may have compatible goals and functionality, the specific details are often different enough that it can be difficult to integrate them. One major problem is how to take information from CAD models and interpret it in a manner that makes sense for CAM. The authors are developing an approach to address this problem in the manufacture of machined parts. Their goal is to develop a general approach that can be used with a variety of CAD and CAM applications.

In this paper, a methodology is presented for taking a CAD model, and translating it into a set of features that make sense for machining applications such as process planning, NC part programming, fixture design and selection, and manufacturability evaluation. The approach involves extracting alternative interpretations of the CAD model as collections of volumetric features that correspond to machining operations, and evaluating these interpretations to determine which one is optimal for the particular application at hand.

Although several approaches have previously been developed for generating interpretations of parts as collections of features, several issues are addressed that have not been adequately addressed by any single existing approach:

(1) For purposes of integrating CAD with CAM, it is

important to be able to obtain features that correspond directly to manufacturing operations — but such features are not provided in many existing approaches. Moreover, no standard schemes are used for representing features, therefore the output of these systems cannot be directly used in downstream computer aided manufacturing applications.

To address this problem, a class of features is used that are expressible as MRSEVs (material removal shape element volumes).¹ MRSEVs are volumetric features corresponding to machining operations on three-axis milling machines; MRSEVs can be defined using EXPRESS (the official STEP information modeling language) and STEP form features. By employing a set of features based on a standard interchange format such as STEP, the authors have attempted to ensure that they are addressing a domain of machinable parts of interest to a large community.

(2) Although many approaches have been developed for recognizing features in solid models of mechanical parts, the absence of a clear mathematical specification for the problem has made it unclear what specific classes of parts and feature interactions can be handled by various existing approaches. In particular, it has proven difficult to capture the changes that occur to feature topology and geometry when they intersect with each other in arbitrary ways.

To address these issues, a formalization is presented of the problem of recognizing any solid that can be

decomposition and composition'. The work of Henderson¹⁷ was seminal in employing expert systems on the feature recognition problem.

In one of the early efforts on feature extraction, Woo¹⁸ proposed a method for finding general depression and protrusion features on a part through decomposing the convex hull of the solid model. The approach had several problems, including being confined to polyhedral models and the existence of certain pathological cases in which the procedure would not converge. The non-convergence of Woo's approach has been solved in recent work by Kim.^{19,20} Kim's approach uses convex volume decompositions to produce alternating sums of volumes and techniques for partitioning the solid to avoid non-convergence. Kim further improved the approach by performing additional mapping of the volumes found to feature templates.

The ability to handle interacting features has become an informal benchmark for feature recognition systems and has been the focus of numerous research efforts. The work of Dong²¹ included the formalization of a feature description language and employed frame-based reasoning algorithms to extract machining features for computer aided process planning. An approach handling feature interactions and intersections was done by Marefat and Kashyap.²² The work built on the representation scheme of Ref. 7 and used a novel combination of expert system and hypothesis testing techniques to extract surface features from polyhedral objects.

Perhaps the most comprehensive approach to date for recognizing features and handling their interactions has been that of Vandenbrande and Requicha.²³ Their method is capable of finding some alternative feature interpretations and is described in the next section.

Other recent work includes feature recognition from 2D engineering drawings,²⁴ via neural network techniques,²⁵ for sheet-metal components,²⁶ and feature modeling by incremental recognition.²⁷

2.2 Generating alternative feature models

The AMPS process planning system²⁸ includes a 'feature refinement' step, in which heuristic techniques are used to combine a set of features into a more complex feature, or split a feature into two or more features. Since the techniques are heuristic in nature, it is not entirely clear when alternative interpretations will be produced.

Vandenbrande and Requicha²³ provide a framework for recognizing a significant class of realistic machining features of interest in process planning using artificial intelligence techniques in combination with queries to a solid modeler. They present a set of feature classes and recognition 'hints' for each class. Hints are extracted from the solid model and classified as to their potential for building feature instances. Like Dong,²¹ a frame-based reasoning system then acts on the hints and attempts to complete a feature frame with information

needed to make a maximal instance of a feature and represent its interaction with other features. While the approach has many advantages, certain types of features will not be recognized if hints are removed or classified as unpromising (and thus are discarded). Further, the number of alternative feature decompositions produced is not controlled.

The first systematic work in the direction of generation of alternative interpretations was done by Karinthe and Nau.²⁹ They described an approach for producing alternative interpretations of the same object as different collections of volumetric features as the result of algebraic operations on the features, and a system for generating alternative interpretations by performing these algebraic operations. However, this system cannot be used directly for CAM applications as there was no direct relation between these features and machining operations, hence some of the interpretations generated by this approach were not feasible from the machining point of view. Further, the algebraic operators were not sufficient to generate all interpretations of interest for machining purposes.

2.3 Evaluating feature models

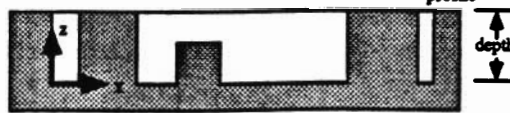
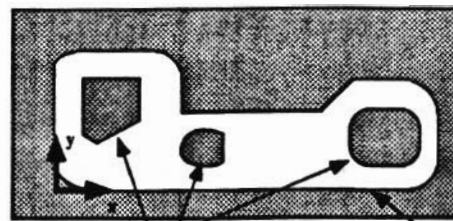
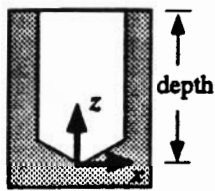
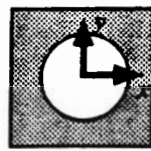
Depending upon the specific CAM application, different evaluation functions have been developed. Extensive research has been done on different aspects of evaluation of operation plans. Mechanistic models have been developed to provide quantitative mappings from machining parameters to various performance measures, such as surface finish and dimensional accuracy.^{28,30-32} Research on machining economics has produced quantitative models for evaluating time and costs related to machining operations.^{33,34}

Researchers have developed several different approaches to evaluate manufacturability.³⁵⁻³⁹ Some of these have been developed for specific application domains, while others have been developed for general domains. Most of these approaches are rule-based: design characteristics which improve or degrade the manufacturability are represented as rules, which are applied to a given design in order to estimate its manufacturability.

3 DEFINITIONS AND NOTATION

3.1 Basic concepts

A solid is a manifold r -set⁴⁰ with analytic bounding surfaces. If R is any solid, then $b(R)$ is the boundary of R , and $i(R)$ is the interior of R . Note that $R = i(R) \cup b(R)$ and that $i(R) \cap b(R) = \emptyset$. If R and R' are solids, then $R \cap^* R'$ is the regularized intersection of R and R' , i.e. the closure of $i(R) \cap i(R')$. Similarly, $R \cup^* R'$ and $R -^* R'$ are the regularized union and regularized difference, respectively.



<u>Attribute of hole</u>	<u>Type</u>
<i>location</i>	point
<i>orientation</i>	vector
<i>depth</i>	positive real number
<i>radius</i>	positive real number

<u>Attribute of pocket</u>	<u>Type</u>
<i>location</i>	point
<i>orientation</i>	vector
<i>depth</i>	positive real number
<i>profile</i>	edge loop
<i>islands</i>	set of one or more islands
<u>Attribute of island</u>	<u>Type</u>
<i>profile</i>	edge loop
<i>height</i>	positive real number

(a)

(b)

Fig. 2. Subclasses of MRSEV holes and MRSEV pockets.

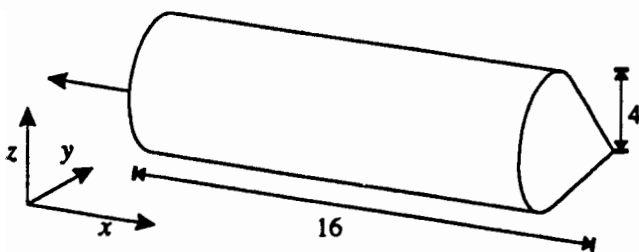
by assigning a specific choice of attribute values. For example, suppose the following attribute values are chosen:

- location** = (16, 10, 4);
- orientation** = (-1, 0, 0);
- depth** = 16;
- radius** = 4.

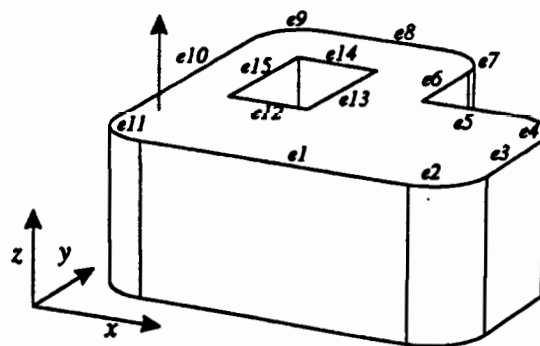
This would define the conical-bottomed hole illustrated in Fig. 3(a). Similarly, the following values would define a MRSEV pocket with a single island as pictured in

Fig. 3(b):

- location** = (0, 0, 1);
- orientation** = (0, 1, 0);
- depth** = 2;
- profile** = { $e_1, e_2, e_3, e_4, e_5, e_6, e_7, e_8, e_9, e_{10}, e_{11}$ };
- islands** = { I_1 };
- profile I_1** = { $e_{12}, e_{13}, e_{14}, e_{15}$ };
- height I_1** = 2.



(a) A MRSEV hole.



(b) A MRSEV pocket.

Fig. 3. MRSEV instances.

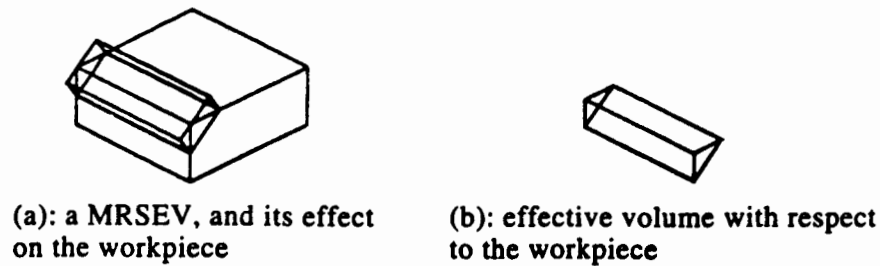


Fig. 5. A pocket MRSEV and its effective volume.

- the non-cutting surface $n(T)$, i.e. the portion of $b(T)$ that is not capable of cutting metal.

For the purpose of locating the tool, choose a particular point p_{td} of T as a datum point. Usually p_{td} will be the tip of the cutting-tool volume, but not always.

To perform the machining operation, one sweeps the tool volume T along some trajectory t , as shown in Fig. 4(b). Given a tool T and a workpiece W , the trajectory t is feasible for T and W only if sweeping T along t does not cause interference problems between the non-cutting surface $n(T)$ and the workpiece. If t is feasible, then the volume created by sweeping T is

$$T_{sw} = \{(p - p_{td}) + q : p \in T \text{ and } q \in t\}$$

as shown in Fig. 4(c). Now, let π be the plane perpendicular to t at the point p_{td} , as shown in Fig. 4(a). Then the solid consisting of all points in T_{sw} that are on or below π represents the material which can be removed by the machining operations. The solid shown in Fig. 4(d) represents the volume which can be removed by a drilling operation. MRSEVs can be used to represent volumes which can be removed during machining. In particular, a MRSEV hole represents the volume which can be removed by a drilling operation, and a MRSEV pocket represents the volume which can be removed by an end or face milling operation. It is worth noting that the 'pocket' MRSEV is used not only to represent what is usually called a pocket, but also to represent a large variety of milled shapes such as slots, steps, profiles, slabs, etc.

3.4 Effective volume of a MRSEV

The volume removed by a MRSEV m from a given workpiece W is not necessarily the volume of m . Instead, it is the effective volume of m with respect to W , which is defined as $\text{eff}(m, W) = W \cap m$. Figure 5 shows a pocket MRSEV and its effective volume with respect to the workpiece.

3.5 Truncation of a MRSEV

Truncation of a MRSEV m with respect to a solid W returns the smallest MRSEV n of m 's type and orientation such that n can remove the volume removed by m from W , i.e. $\text{eff}(n, W) = \text{eff}(m, W)$. An example of MRSEV truncation is shown in Fig. 6.

3.6 MRSEV models

Let P be the given part and S be the given stock. Define a MRSEV Model of P and S to be a finite set of MRSEV instances M having the following properties:

1. If one subtracts the MRSEVs in M from S one gets P , i.e. $S - \cup_{m \in M} m = P$.
2. No MRSEV in M is redundant, i.e. for every MRSEV $l \in M$, $S - \cup_{m \in M - \{l\}} m \neq P$.

Intuitively, a MRSEV model is an interpretation of the delta volume as a set of machining features. For example, the set $\{h1, h2, s1, s2\}$ shown in Fig. 7 is a MRSEV model.

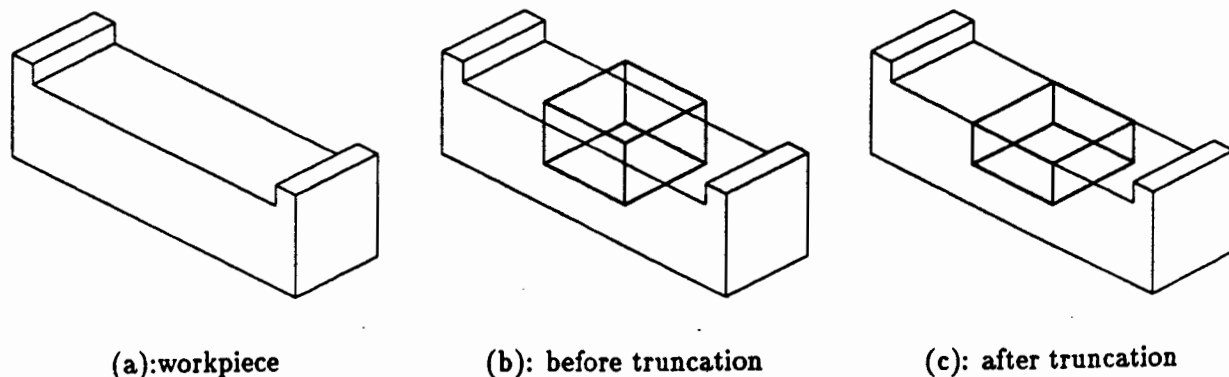


Fig. 6. An example of MRSEV truncation.

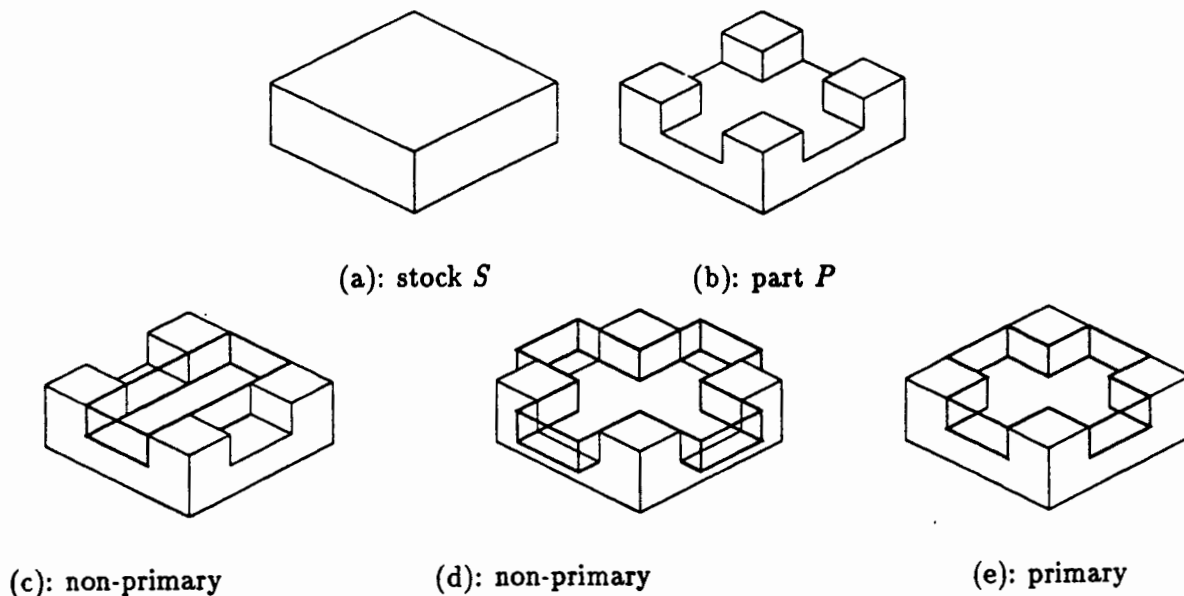


Fig. 9. Example of primary and non-primary MRSEVs.

effective volume as m (i.e. if $m \subset n$ then $\text{eff}(n, S) = \text{eff}(m, S)$).

- Every valid MRSEV n that is contained in m (and has the same type and orientation) has a smaller effective volume (i.e. if $n \subset m$ then $\text{eff}(n, S) \subset \text{eff}(m, S)$).

An arbitrary part and stock may still present a problem because they may give rise to an infinite number of possible primary MRSEVs. For realistic parts, most of these possibilities will not correspond to reasonable machining operations and removal volumes. Consider the class of primary MRSEVs with the following characteristics:

- For any primary hole MRSEV h , the delta volume contains either a subsurface of the h cylindrical side surface or the h entire ending surface;
- For any primary pocket MRSEV p , either a subsurface of the p bottom face is present in the delta volume, or p is a through pocket with subsurfaces of two or more non-parallel planar side faces or one non-planar side face present in the delta volume.

The output of the MRSEV recognizer is a primary MRSEV set, \mathcal{M} : a finite set whose elements are all primary MRSEVs satisfying the characteristics enumerated above. In the context of this paper, a MRSEV recognition algorithm is complete if it returns the set of all primary MRSEV instances with these properties that appear in any of the MRSEV models of P and S (if no such MRSEV models exist, the algorithm reports so).

4.1 MRSEV recognition

Given the specifications for the MRSEV recognition problem, one can outline the algorithms for solving it.

Start with a solid model of the part P and construct all instances of primary MRSEVs that can be built from the geometric and topological information contained in the boundary-representation⁴⁹ of P . Proceeding from the observation that every valid primary MRSEV instance m must contribute to some face of the delta volume, the set of primary MRSEV instances can be found by traversing the faces of the delta volume and instantiating those primary MRSEVs capable of covering all or a portion of each face. A high-level description of the MRSEV recognition algorithm can be given as follows:

RECOGNIZE_MRSEVs:

INPUT: solid models of a part P and stock S

OUTPUT: a primary MRSEV set, \mathcal{M} .

- For each face f of $S - P$ do:
- If f is a concave cylindrical face, f might be a subsurface of the side of a MRSEV hole or a subsurface of a round side face of a through pocket. Construct the possible primary instances of MRSEVs that might have created f as described below in RECOGNIZE_HOLES and RECOGNIZE_POCKETS. If f is a convex cylindrical face, f might be a subsurface of a round side face of a through pocket. Construct the instances of primary MRSEVs capable of creating f (RECOGNIZE_POCKETS).
- If f is a planar face, f might be a subsurface of the bottom surface of a non-through pocket or a subsurface of a side surface of a through pocket (RECOGNIZE_POCKETS).
- If f is a concave conical face, f may be the end surface of a hole (RECOGNIZE_HOLES).
- Return, \mathcal{M} , the set of features built.

Depending on the type of surface, calculate a parameterization for each possible primary MRSEV that

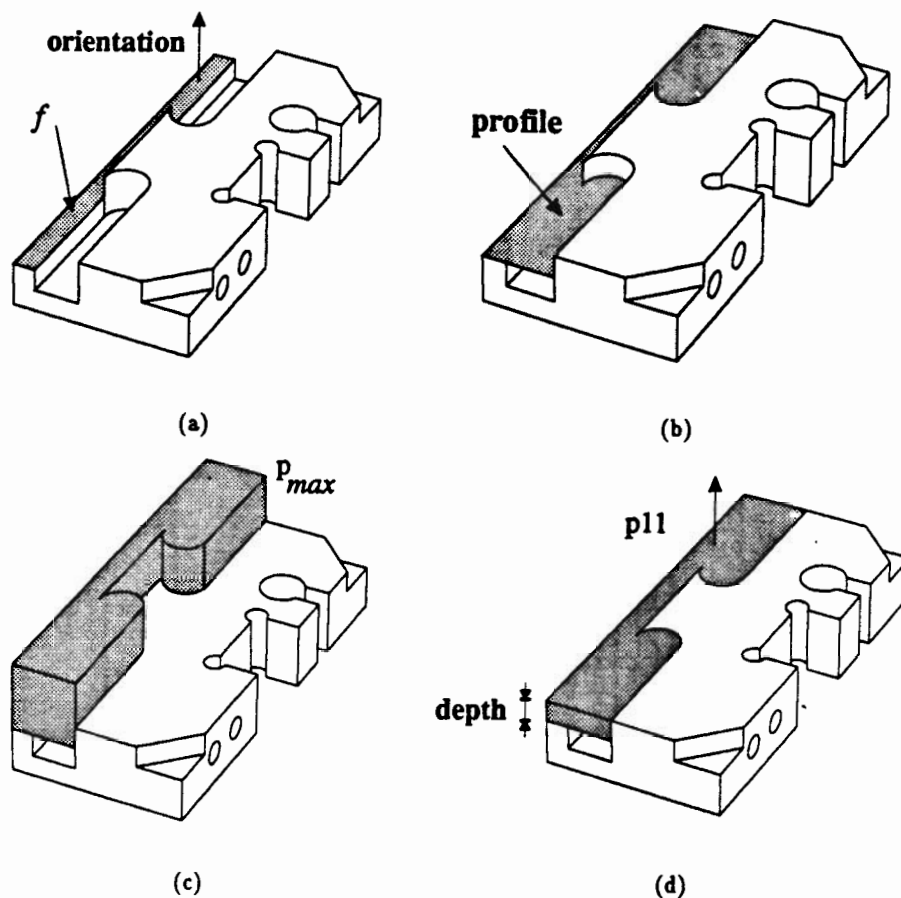


Fig. 11. Construction of a MRSEV pocket.

the part P created by an instance of a pocket MRSEV, there are two possibilities:

1. A face f could be a subsurface of the planar bottom surface of a pocket MRSEV, as shown in Fig. 11(a).
2. A face f could be a subsurface of a side face of a pocket MRSEV which extends through the part, possibly a corner radius or a pocket wall. This type of feature is often called a through pocket, an example of which is feature p_7 shown in Fig. 12.

In the first case, an orientation for the pocket MRSEV is determined from the surface normal of f , as shown in Fig. 11(a). In the second case where the feature is a through pocket, there are two possible MRSEV pocket instances having opposite orientations. These orientations can be determined from either the axis of the cylindrical surface or the cross product of the normal vectors of f and another planar surface f' elsewhere in the delta volume.

For this class primary MRSEV features, the pocket profile can be computed from the projection of the part faces that lie above (with respect to the orientation) the plane containing the bottom surface of the pocket, as illustrated in Fig. 11(b), and an arbitrary location for the

pocket based on the profile chosen. In the second case, where the pocket extends through the part and there is no bottom surface present in the delta volume, an arbitrary location can be chosen for the projection plane and all of the part faces are mapped onto it. In this way, it is ensured that the MRSEV pocket is accessible in the direction of its orientation and the maximal pocket profile capable of creating these surfaces can be calculated.

Given the profile, an instance of a maximal MRSEV pocket p_{max} can be created, as shown in Fig. 11(c). In the case of a through pocket, two maximal MRSEV pocket instances are created. Truncate p_{max} to obtain the primary MRSEV pocket, as shown in Fig. 11(d), with a depth sufficient to extend the feature instance outside the stock. Features p_7 and p_8 in Fig. 12 show examples of through pocket MRSEVs.

The MRSEV holes found for the part in Fig. 1 are shown in Fig. 13.

Example. For the part in Fig. 1, Figs 12 and 13 shows the various MRSEVs identified by the algorithm. In this case, the MRSEV set is

$$\mathcal{M} = \{p_1, p_2, p_3, p_4, p_5, p_6, p_7, p_8, p_9, p_{10}, p_{11}, p_{12}, p_{13}, p_{14}, p_{15}, h_1, h_2, h_3, h_4, h_5, h_6, h_7, h_8\}.$$

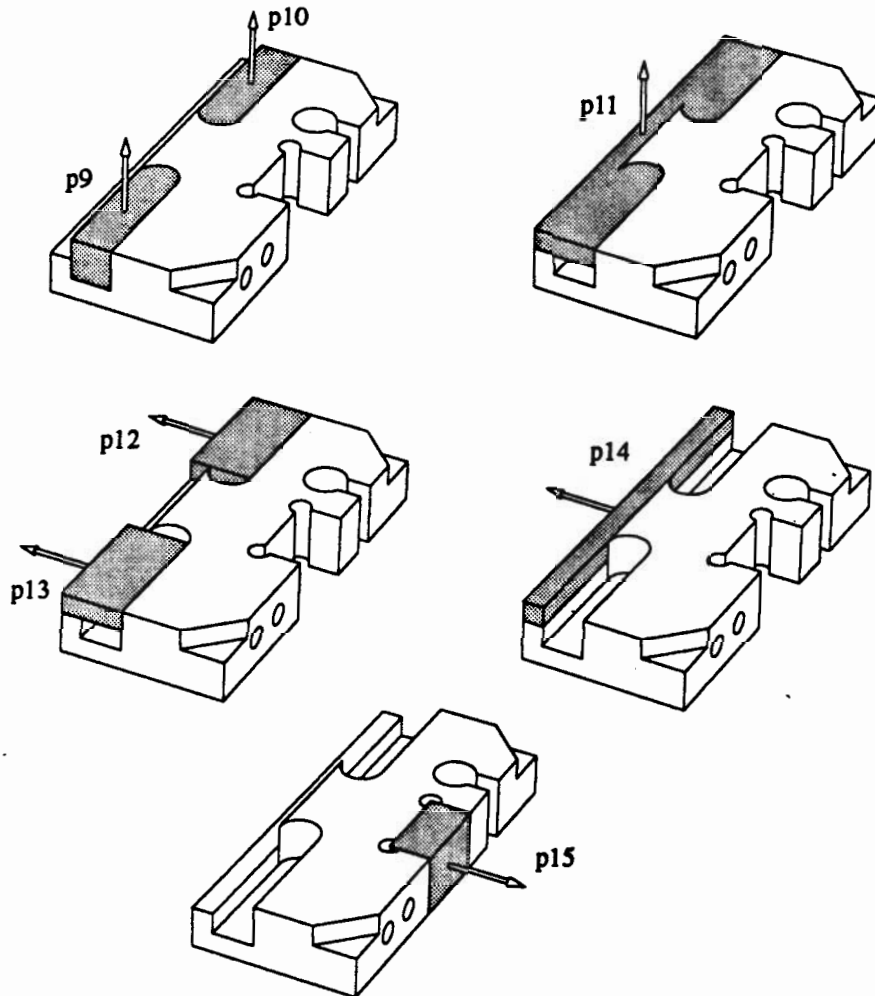


Fig 12. (Continued.)

covers found by FIND_COVERS, this algorithm finds one or more MRSEV Models M such that the effective volumes of the MRSEVs in M are identical to the volumes in the irredundant cover. Whenever GENERATE_MODELS finds a MRSEV model, it evaluates it for the given CAM application and compares it with the current best model.

- **EVALUATE_MODEL.** This algorithm evaluates a MRSEV model for a specific CAM application—described in the next section.

First the FIND_BEST_MODEL algorithm is presented. This algorithm computes the set \mathcal{V} of effective volumes with respect to the stock S , and then splits \mathcal{V} into two parts. One part, V , contains each volume that is not subsumed by the other volumes in \mathcal{V} . These volumes are guaranteed to be in every irredundant cover for \mathcal{V} . The other part, $\mathcal{V} - V$, contains each volume that is subsumed by the other volumes in \mathcal{V} . These volumes may appear in some irredundant covers for \mathcal{V} , but will not appear in all of them. To compute the irredundant covers and find the best one. FIND_BEST_MODEL invokes a subroutine called FIND_COVERS.

Algorithm 5.1 FIND_BEST_MODEL(\mathcal{H})

INPUT: a primary MRSEV set, \mathcal{H} .

OUTPUT: **best_model**, the best MRSEV model as calculated by an evaluation function.

$$\mathcal{V} = \{\text{eff}(m, S) : m \in \mathcal{H}\}$$

$$V = \{v : v -^* \bigcup_{q \in \mathcal{V} - \{v\}} (q) \neq \emptyset\}$$

$$\text{best_model} = \emptyset$$

$$\text{best_eval} = \infty$$

for every $C \in \text{FIND_COVERS}(\mathcal{V} - V, V)$, do

(**best_eval**, **best_model**)

= GENERATE_MODELS($C, \emptyset, \text{best_eval}, \text{best_model}$)

return(**best_model**).

For the MRSEVs shown in Figs 12 and 13, the set of effective volumes with respect to the stock is:

$$\mathcal{V} = \{v1, v2, v3, v4, v5, v6, v7, v8, v9, v10, v11, v12, v13, v14, v15, v16\}$$

where

$$v1 = \text{eff}(p1, S) = \text{eff}(p3, S)$$

$$v2 = \text{eff}(p2, S) = \text{eff}(p4, S)$$

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(i.e.  $\cup (V - \{v\}) = \cup V$ )
return  $\emptyset$  //  $V$  is redundant
if the delta volume is completely covered by  $V$ 
  (i.e.  $\Delta \subseteq \cup V$ )
  return  $\{V\}$  // we have found an irredundant cover
if volumes in  $V$  and  $X$  cannot cover the delta volume
  (i.e.  $\Delta \not\subseteq \cup (V \cup X)$ )
  return  $\emptyset$  //  $V$  is not feasible
choose a volume  $v$  in  $X$ 
return(FIND_COVERS( $X - \{v\}$ ,  $V \cup \{v\}$ )
       $\cup$  FIND_COVERS( $X - \{v\}$ ,  $V$ ))

```

For the MRSEVs shown in Figs 12 and 13, FIND_COVERS finds following four covers:

$V1 = \{v1, v2, v3, v4, v5, v6, v10, v15, v16\}$

$V2 = \{v1, v2, v3, v4, v5, v6, v7, v15, v16\}$

$V3 = \{v1, v2, v3, v5, v6, v7, v11, v12, v13, v15, v16\}$

$V4 = \{v1, v2, v3, v5, v6, v10, v11, v12, v13, v15, v16\}$

Each time that FIND_COVERS finds an irredundant cover for the delta volume, the next step is to generate one or more MRSEV models from this cover. This is done by using the depth-first branch-and-bound algorithm GENERATE_MODELS described below. GENERATE_MODELS takes four arguments, V and N , best_model and best_eval. N is the partial MRSEV model that has been built up already, V is the set of volumes from which MRSEVs need to be generated in order to finish the N cover, best_model is the best MRSEV model that has been seen so far, and best_eval is its evaluation function value. GENERATE_MODELS is called recursively to remove volumes from V , and to explore alternative completions of the N cover. For each MRSEV model that GENERATE_MODELS generates, it evaluates the MRSEV model by calling EVALUATE_MODEL described in the next section.

If good MRSEV models are generated and examined first, then one need not examine any MRSEV model that is not expected to be better than the current best. Use heuristic $h(N, V)$ to estimate the lower bound of the evaluation function value. This heuristic depends on the particular CAM application. An example of such a heuristic is described in the next section.

Algorithm 5.3 GENERATE_MODELS(V, N , best_eval, best_model)

INPUT: V , a partial set cover; N , a partial MRSEV model, best_eval, best_model.

OUTPUT: best_eval; best_model

```

if  $h(N, V) \geq \text{best\_eval}$ 
  return (best_eval, best_model)
  //  $N$  is unpromising
  // The pruning heuristic  $h(N, V)$  estimates the
  // lower bound of best_eval resulting
  // from MRSEVs in set  $N$ . This heuristic is
  // described in the next section.

```

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if  $V = \phi$ 
  // we have found a MRSEV model
  if EVALUATE_MODEL( $N$ ) < best_eval
    // EVALUATE_MODEL returns evaluation function
    // values for a specific application domain. How
    // this evaluation is performed is described in the
    // next section.
    best_eval = EVALUATE_MODEL( $N$ )
    best_model =  $N$ 
  return (best_eval, best_model)
else
  choose a volume  $v$  in  $V$ 
  let  $Assc$  be the set of all MRSEVs in  $\mathcal{M}$  having
   $v$  as their effective volume
  (i.e.  $Assc = \{l : \text{eff}(l, S) = v\}$ )
  for each MRSEV  $n \in Assc$ 
    (best_eval, best_model) = GENERATE_MODELS
    ( $V - \{v\}$ ,  $N \cup \{n\}$ , best_eval, best_model)
  return(best_eval, best_model)

```

The efficiency (but not the correctness) of GENERATE_MODELS depends on the order in which volumes v are chosen from V . The heuristic is to choose the one that has the minimum number of MRSEVs associated with it, i.e. to choose $v \in V$ that minimizes the cardinality of the set $\{l : \text{eff}(l, S) = v\}$. The efficiency also depends on the order in which it examines the MRSEVs in $Assc$. The heuristic is to examine MRSEVs $n \in Assc$ in order of increasing value of the pruning heuristic $h(N \cup \{n\}, V - \{v\})$.

Example. For the MRSEVs shown in Figs 12 and 13, the MRSEV model

$M = \{p3, p4, p5, p9, p10, p11, p15, h1, h2, h7, h8\}$

produces the lowest value of the evaluation function (described in next section). This model was generated from cover $V3$.

6 EVALUATING MRSEV MODELS

Depending upon the CAM application, one is given some evaluation function. In most of the cases, one is interested in finding the MRSEV model which optimizes the value of this evaluation function. For example, if one wants to use the MRSEV model for process planning, the evaluation function could be production cost, production time or a combination of these.

Besides optimizing the evaluation function value, most CAM applications will require that the MRSEV model should satisfy some additional constraints. For example, in the case of process planning, operations associated with the MRSEV model should be capable of meeting the tolerance requirements. Moreover for a MRSEV model to be useful for process planning, there must exist a sequence of machining operations such that during all stages of machining, the intermediate work-piece geometry is suitable for fixturing and setup.

of the set $\{\vec{d}(n) : n \in N\}$, where $\vec{d}(n)$ is the unit orientation vector for MRSEV n ,
 $L_T(n)$ = lower bound on the time required to machine MRSEV n {this is the time required to machine the irredundant portion of the effective volume of n [i.e. $\text{eff}(n, S) - \cup(V) - \cup_{l \in N - \{n\}} (\text{eff}(l, S))$]}
 β = an estimate of the auxiliary time as a fraction of the machining time (the authors use $\beta = 0.2$).

7 IMPLEMENTATION

A proof-of-concept implementation of these algorithms has been built in C++ using version 1.5.1 of Spatial Technologies' ACIS[®] solid modeling system in conjunction with the NIH C++ Class Library developed at the National Institutes of Health. Also being employed in the authors' development efforts are Ithaca Software's HOOPS[®] Graphics System and the Tcl/Tk embeddable command language and user interface toolkit developed at the University of California at Berkeley.

The current MRSEV recognizer constructs instances of hole and pocket MRSEVs as outlined in Refs 50 and 51 with the exception of some cases of through pockets. Implementation for general through pockets was restricted by the current version of the ACIS[®] application procedural interface which, at the time of this writing, the authors are extending to provide the needed functionality. The algorithms for building MRSEV models operate on any type of volumetric features.

8 FUTURE WORK

8.1 Recognizing MRSEVs

Near-term goals include incorporating a more sophisticated definition of accessibility, extending the results and implementation to include a wider class of MRSEVs, and exploring techniques to reduce computational costs.

8.2 Generating redundant MRSEVs

If one uses MRSEVs to represent the swept volume of the cutting portion of the tool, then one will need to take into account the possibility of using different tools when one generates alternative MRSEV models. For example:

1. It is often desirable to use a roughing operation to remove a volume of material followed by a finishing operation in which the swept volume of the tool completely subsumes the removal volume of the roughing operation. Examples are: (i)

making a hole by drilling and then reaming the hole, (ii) making a slot with a roughing end mill and then finishing the slot with a slightly larger finish end mill. It follows that redundant MRSEVs must be considered at some point. The redundant MRSEVs should certainly be generated before a cutting order is established and cost is estimated.

2. If one is cutting a pocket whose outline is an hourglass shape (or any shape with a bottleneck in it), the cost-effective method is to use a large tool to cut the bottom and top of the hourglass and a small tool to cut the narrow part in the middle where the large tool would not fit. Using the small tool to cut the entire pocket would take too much time. Thus, a MRSEV decomposition must include three MRSEVs for cutting the pocket. The authors are exploring techniques for identifying bottlenecks in a MRSEV, and splitting the MRSEVs if bottlenecks occur.
3. For pocket MRSEVs, in some cases one assigns an arbitrary tool radius. The authors are working on developing some heuristic rules to determine tool radius values when generating a MRSEV model.

8.3 Incorporating setup and fixturing aspects in the evaluation framework

The current approach does not deal with considerations involved with setup and fixturing issues. When evaluating MRSEV models (see Section 6), one needs to make sure that all intermediate workpiece shapes can be clamped. Addressing this issue is a major problem for future work.

9 CONCLUSIONS

The authors have described their work toward the goal of developing a general approach to integrating CAD and CAM applications for the manufacture of machined parts. Their approach involves taking a CAD model, extracting alternative MRSEV models for that CAD model, and evaluating the MRSEV models to determine which one is optimal for the particular CAM application at hand. Some of the primary characteristics of their approach are as follows:

1. While various CAD and CAM applications may have compatible goals and functionality, their specific details are often different enough that integrating them can prove difficult. To address this problem, the authors' approach encompasses many parts of direct interest to machining and manufacturability evaluation application and employs the MRSEV feature library, offering the possibility of compliance with the well known STEP standard.

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