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Development of Machining Alternatives, Based on MRSEVs

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ABSTRACT

One missing link between CAD and CAM is the lack of a systematic methodology for generating and evaluating alternative ways to manufacture a proposed design. To address this problem, we are developing a systematic approach for generating and evaluating alternative ways to manufacture machined parts, in order to provide information to the designer about the manufacturability of the proposed design, and information to the process engineer about how best to machine the part. This paper describes our overall approach, and how MRSEVs (Material Removal Shape Element Volumes, a STEP library of machining features) can be used to support it.

INTRODUCTION

One of the missing links between CAD and CAM is the virtual absence of any systematic methodology for generating and evaluating the alternative ways to manufacture a proposed design. Most integrated CAD/CAM systems try to generate a single process plan for a given design—but in general, there may be several alternative ways to manufacture the design, and these alternatives should be generated and examined, to determine how well each one balances the need for a quality product against the need for efficient manufacturing. We are developing methods for solving this problem in the domain of machined parts.

Overview of Approach

Our approach involves representing the design as a collection F of *machining features*, volumetric features that correspond to machining operations. By examining the features in F, we can identify precedence constraints requiring that some features be machined before or after other features. If the constraints are contradictory, then F does not correspond to any feasible way to machine the design. Otherwise, these constraints impose a partial ordering on the features in F, and each total ordering consistent with the partial ordering represents a possible machining sequence for the design. By using mathematical and empirical models of the various machining processes, we can estimate the time and cost required to machine the features in F, and predict the achievable machining tolerances and surface finishes.

In general, there may be several alternative representations of the design as different collections of machinable features, corresponding to different ways to machine the part. Which of these alternatives is most preferable will depend on the part's dimensions, tolerances, and surface finishes, the availability and capabilities of machine tools and tooling, and fixturability considerations. We are developing a methodology capable of systematically generating and evaluating the alternatives, in order to find the ones that produce the most preferable machining plans.

The results of such an analysis can potentially be used for two purposes: (1) to give the production engineer information about what processes and process parameters are most desirable over the various ways in which the part might be machined; and (2) to give the product designer a better understanding of whether and how the design might be changed to improve its manufacturability.

Representation Using MRSEVs

In order to allow this approach to be used with a number of different CAD/CAM systems, we are interested in representing the machining features using a standard interchange format such as STEP. Each of our machining features is a pair $f = (r, a)$, where r is the volume of material removed by the operation, and a is the volume of space needed for access during the machining operation—so to represent f, we need ways to represent both r and a.

To represent the removal volume r, we can use a preexisting library of STEP features, namely, Kramer's MRSEVs (Material Removal Shape Element Volumes) [18, 19]. These are volumetric features corresponding to machining operations on 3-axis milling machines. MRSEVs can be defined using EXPRESS (the official STEP information modeling language) and STEP form features. Kramer has already done this for a subset of the MRSEV library, and has defined the rest using an EXPRESS-like language.

Although there is no library of STEP features to represent accessibility volumes, it should be possible to define one, in a manner similar to the MRSEV library. We believe that doing so would be useful not only for our work, but for process planning in general.

RELATED WORK

Feature-based approaches have been very popular in a variety of CAD/CAM implementations, but different people have used the term to mean different things [27, 11, 16, 7]. Significant amounts of work have been directed towards defining sets of form features to serve as a communication medium between design and manufacturing—but at present, most researchers are convinced that a single set of features cannot satisfy the requirements of both of these domains. The recent trend seems to be toward defining sets of features with specific application domains in mind (such as machining, assembly, inspection, etc.). For the machining domain, most researchers agree that volumetric features are preferable to surface features, although certain additional information about the surfaces is needed (for example, to determine accessibility and tool approach directions).

Recognizing Machining Features

To obtain machining features from a CAD model, there are three primary approaches. In ***human-supervised feature recognition***, a human user examines an existing CAD model to determine what the manufacturing features are [2]. In ***automatic feature recognition***, the same feature recognition task is performed by a computer system [5, 29, 25, 6, 13]. In ***design by features***, the designer specifies the initial CAD model in terms of various form features which translate directly into the relevant manufacturing features [26, 28, 12]. Many examples exist of each of these approaches. However, their scope is often limited by the feature definitions and the object classes of their individual domains; and it is often unclear what specific classes of objects, features, and feature interactions can be handled by various techniques.

Generating Alternatives

Hummel [11] and Mantyla [21] present examples of multiple feature representations of the same object. However, these papers do not describe a system or methodology for generating multiple feature models.

Hayes's MACHINIST system [10] can identify certain cases in which one feature needs to be made before another. However, its representation of features is not adequate for all aspects of process planning. For example, if it decides that some hole needs to be made before some slot, it does not automatically update the dimensions of the hole or the slot—information which would be needed for process selection.

The AMPS process planning system [3] 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's [29] system uses hints or clues to identify potential features in the boundary representation of the part. It can identifying interacting features (e.g., two intersecting slots), and produces alternative feature interpretations in certain cases. Although the approach is computationally rigorous, the work does not formalize the complete class of interactions within its capabilities. Thus, it is hard to determine what all the interpretations it produces are, and arbitrarily complex feature interactions may pose problems.

The first systematic work on generation of alternative interpretations was done by Karinthi and Nau [14, 15]. They describe algebraic operators for producing alternative interpretations of the same object as different collections of machining features, and a system that uses these operators to generate alternative interpretations. However, their operators and features have no direct relation to machining operations—so they generate some interpretations that are not feasible from a machining point of view, and fail to generate others that are feasible. Also, their work does not deal with time orderings among the features, as would be needed in process plans.

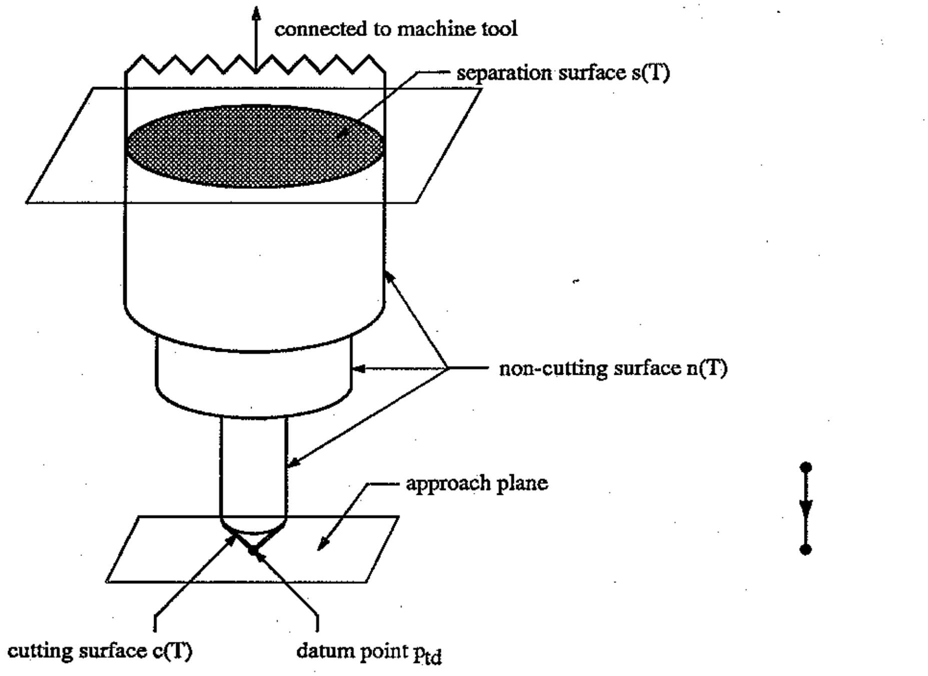
Machinability Evaluation

Because of the need for quality assurance on the shop floor, extensive research has been done on evaluating of machinability for a given design. Much of the data relevant for machining operation planning is available in machining data handbooks such as [20]. In addition, mechanistic models have been developed to provide quantitative mappings between machining parameters (such as cutting speed, feed, and depth of cut), to the performance measures of interest (such as surface finish and dimensional accuracy) [31]. Research on machining economics has produced quantitative models for evaluating costs related to machining operations [1, 30]. Optimization techniques have been applied to these quantitative models to seek the machining parameters which minimize the variable cost, or maximize the production rate and profit rate associated with machining operations.

DEFINITIONS

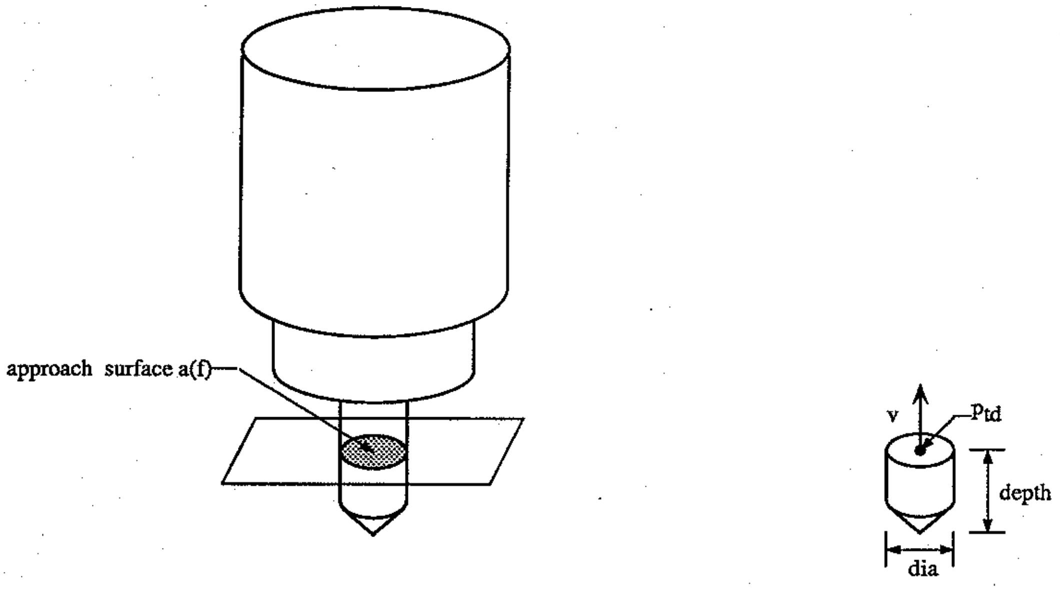
Basic Concepts

A *solid* is any regular, semi-analytic subset of three-dimensional Euclidean space. If R is any solid, then $b(R)$ is the *boundary* of R, and $\iota(R)$ is the *interior* of R. Note that $R = \iota(R) \cup b(R)$ and that $\iota(R) \cap b(R) = \emptyset$. If R and R' are solids, then $R \cap^* R'$ is the *regularized intersection* of a and b, i.e., the closure of $\iota(R) \cap \iota(R')$. Similarly, $R \cup^* R'$ and



(a) drilling tool (T)

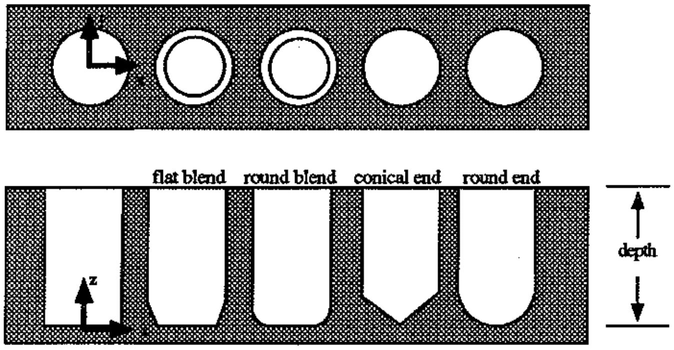
(b) a trajectory (t)



(c) tool swept volume (T_{SW})

(d) hole

Figure 1: A cutting tool, and the resulting removal volume.



Attribute of a hole	Type
location	point
orientation	vector
depth	positive real number
radius	positive real number
end	end condition

Figure 2: MRSEV Holes.

$R -^* R'$ are the *regularized union* and *regularized difference*, respectively. The basic idea of these regularized operations is to make sure the object includes all its faces, and to remove dangling edges and faces.

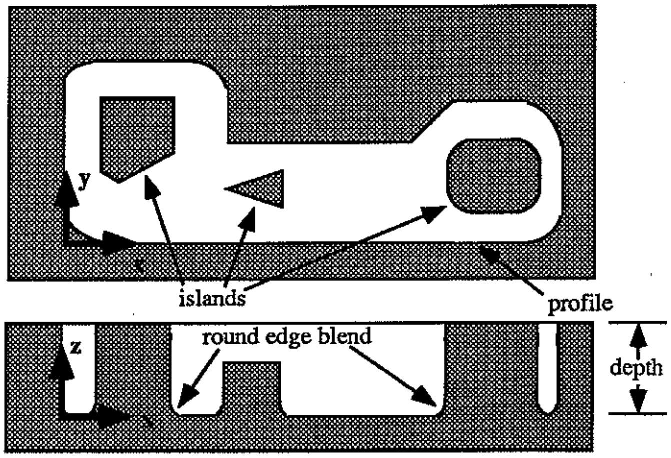
A *machined part* (or just a *part*) is the finished component to be produced as a result of a set of machining operations on a piece of *stock*, i.e., the raw material from which the part is to be machined. We will represent both the part and the stock as geometric solids. We use term *workpiece* to describe the state of stock after applying a subset of operation sequences.

Throughout this paper, we let P be a solid representing a part, and S be a solid representing the stock from which P is to be made. The *delta volume* (i.e., the volume to be machined), is the solid $\Delta = S - P$.

Removal Volumes and Accessibility Volumes

To perform a machining operation, one starts out with a rotating cutting tool. The cutting tool is mounted on a large machine tool, and the total volume occupied by the cutting tool and the machine tool is quite large. But we will only be interested in some small portion of this total volume, namely the portion that actually gets close to the workpiece. We will call this portion the *tool volume*, and we will denote it by T. The boundary $b(T)$ is naturally partitioned into three pieces, as shown in Fig. 1(a):

- the *separation surface* $s(T)$, i.e., the portion of $b(T)$ that connects to the rest of the machine tool;
- the *cutting surface* $c(T)$, i.e., the portion of $b(T)$ that is capable of cutting metal;
- the *non-cutting surface* $n(T)$, i.e., the portion of $b(T)$ that is not capable of cutting metal.



Attribute of a pocket	Type
location	point
orientation	vector
depth	positive real number
profile	edge loop
bottom blend	edge blend
islands	set of one or more islands
Attribute of mesa_island	**Type**
location	point
profile	edge loop
location angle	real number
bottom blend	optional edge blend
height	positive real number

Figure 3: MRSEV Pocket with islands.

For the purpose of locating the tool, we will 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. 1(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. 1(c). Now, let π be the plane perpendicular to t at the point p_{td}, as shown in Fig. 1(a). Then the machining operation's *removal volume* is the solid r consisting of all points in T_{sw} that are on or below π. The machining operation's *accessibility volume* is the set a of all points in T_{sw} that are on or above π.

REPRESENTING REMOVAL VOLUMES USING MRSEVS

Each removal volume r can be considered to be a member of a parameterized class of removal volumes that is characterized by the shape and trajectory of the cutting tool. To represent these classes of removal volumes, Kramer [18, 19] has developed a library of Material Removal Shape Element Volumes (MRSEVs), which represent the shapes of volumes that can be removed by machining operations on a 3-axis machine tool, using general-purpose cutting tools.

MRSEVs can be defined using EXPRESS and STEP form features. Kramer has already done this for a subset of the MRSEV library, and has defined the rest using an EXPRESS-like language.

The primary types of MRSEVs in Kramer's MRSEV library include linear swept features, such as holes, pockets and pockets with islands; ramps; edge cut features; and rotational pockets. As examples, the MRSEVs for holes and pockets are shown in Figs. 2 and 3, respectively. An *instance* of a MRSEV is the removal volume produced by choosing specific values for the MRSEV parameters. If the removal volume r is an instance of some MRSEV m, then we define $MRSEV(r) = m$.

Suppose we are given a part P and stock S. We define a *MRSEV Model* of P and S to be any set of MRSEV instances R having the following properties:

1. If we subtract the removal volumes in R from S, we get P; i.e., $S -^* \cup^*_{r \in R} r = P$.
2. No removal volume in R is redundant, i.e., for every removal volume $q \in R$, $S - \cup^*_{r \in C -^* \{q\}} r \neq P$.

Intuitively, a MRSEV model is an interpretation of the delta volume as a set of removal volumes. For example, the set $\{s11, s12, s13, h10\}$ shown in Fig. 5(a) is a MRSEV model of the part and stock shown in Fig. 4.

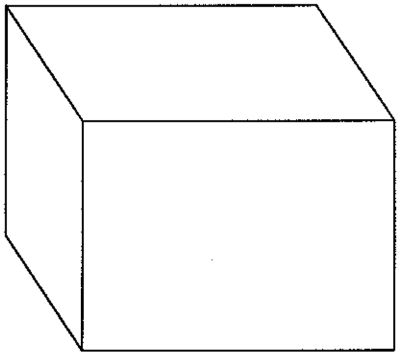
Let r and r' be any two distinct removal volumes in some MRSEV model. Then r and r' *intersect* each other if $r \cap^* r' \neq \emptyset$. Furthermore, r and r' are *adjacent* if $r \cap r' \neq \emptyset$ and $r \cap^* r' = \emptyset$.

FINDING AN INITIAL MRSEV MODEL

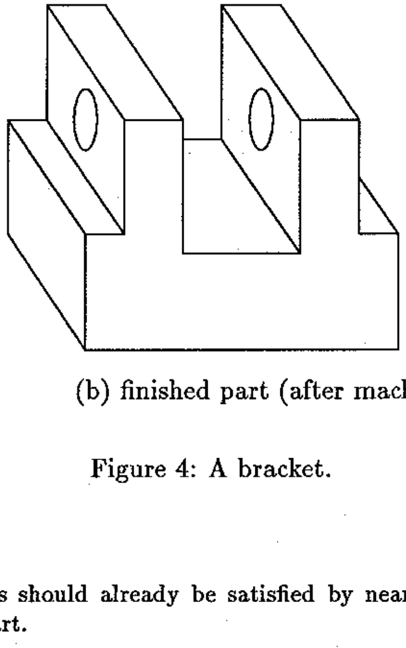
Although many approaches have been developed for recognizing machinable features in solid models of mechanical parts, the scope of each approach is often limited by the feature definitions and the object classes of their individual domains. It is often unclear what specific classes of objects, features, and feature interactions can be handled by various approaches, making it difficult to evaluate their overall utility.

As a first step toward addressing this difficulty, let P and S be any part and stock for which there exists at least one MRSEV model R satisfying the following restrictions:

1. every removal volume in R is either a hole or a pocket;
2. for every hole in R, a subface of its cylindrical face or ending surfaces are present in the delta volume;
3. for any pocket in R, either a subface of its bottom face is present in the delta volume, or else it is a through pocket and at least two of its non-parallel planar side faces are present in the delta volume.



(a) stock (before machining)



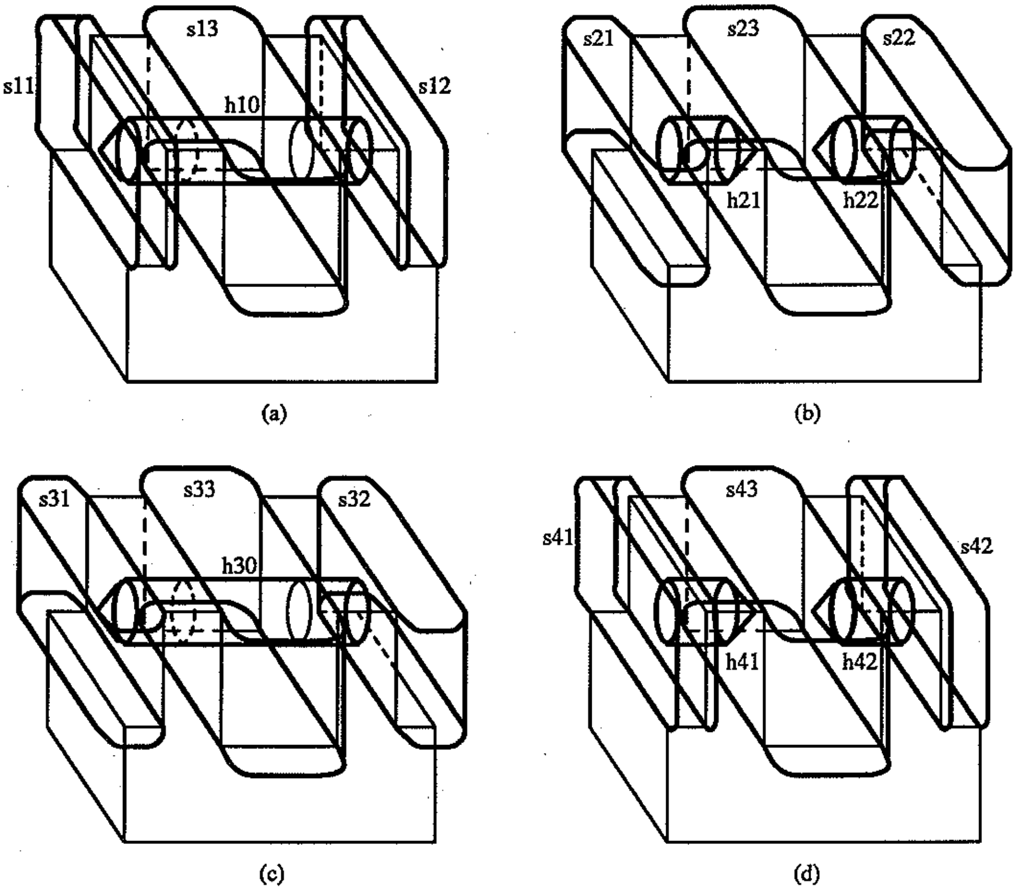
(b) finished part (after machining)

Figure 4: A bracket.

Of the above restrictions, the first one is significant since it excludes us from considering some of the MRSEVs (grooves, ramps, and a few others). However, the second and third restrictions should already be satisfied by nearly any reasonable part.

We have developed a procedure capable of finding a MRSEV model for any part P and stock S that satisfy the above restrictions. The procedure is provably complete over the set of all such P and S, even if the features intersect with each other in arbitrarily complex ways. For example, our procedure can handle each of the objects shown in Figs. 6 without any difficulty. The details of the procedure appear in [24].

The primary limitation of this procedure is that it 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, islands and other characteristics, in order to realistically describe a non-trivial set of mechanical parts. In the near future, we intend to implement the procedure, and extend our results and procedure to include other MRSEVs.



(a) (b) (c) (d)

Figure 5: Four MRSEV models of the bracket shown in Fig. 4.

GENERATING EQUIVALENT MRSEV MODELS

If two MRSEV models R and R' represent the same part and stock, then we say that they are *equivalent*, or that they are *reinterpretations* of each other. For example, all of the MRSEV models in Fig. 5 are equivalent.

Given a MRSEV model R, other MRSEV models equivalent to R can be produced by manipulating the removal volumes in R. For example, Fig. 5(b) can be produced from Fig. 5(a) by splitting the hole h10, and Fig. 5(c) can be produced from Fig. 5(a) by reorienting the shoulders s11 and s12. Below, we briefly describe several operators for producing equivalent MRSEVs (for more detailed descriptions, see [8]). In each case, r is a removal volume in R.

ENLARGE(r). Try to find a MRSEV instance r' that subsumes r, by extending r into some adjacent removal volume $q \in R$. If such an r' exists, then return the MRSEV model $R - R' \cup \{r'\}$, where $R' = \{q \in R : r' \text{ subsumes } q\}$ (in particular, note that $r \in R'$).

REDUCE(r). Try to find a MRSEV instance r' subsumed by r, by truncating r at some intersecting removal volume $q \in R$. If such an r' exists and is not subsumed by some member of $R - \{r\}$, then return the MRSEV model $R - \{r\} \cup \{r'\}$.

REORIENT(r). Try to find a MRSEV instance r' that has a different orientation from r, but which removes the same material from the part. If such an r' exists, then return the MRSEV model $R - \{r\} \cup \{r'\}$.

SPLIT(r). Try to split r into two MRSEV instances r' and r''. If such MRSEV instances exist and are not subsumed by members of $R - \{r\}$, then return the MRSEV model $R - \{r\} \cup \{r', r''\}$.

COMBINE(r', r''). This operator is the inverse of the SPLIT operator.

As an example, suppose we start with Interpretation 1 of Fig. 7. Then Interpretation 2 can be generated by truncating h with respect to $s1$, Interpretation 3 can be generated by reorienting f, and Interpretation 4 can be generated by enlarging h with respect to $s3$.

By starting with a given MRSEV model R and applying the operators described above, it is possible to produce other MRSEV models equivalent to R. In [8], we describe a state-space search algorithm that will generate all MRSEV models that can be produced in this manner. As an example, Fig. 7 shows a portion of the state space that would be generated by this algorithm, starting from any one of the interpretations shown in Fig. 5.

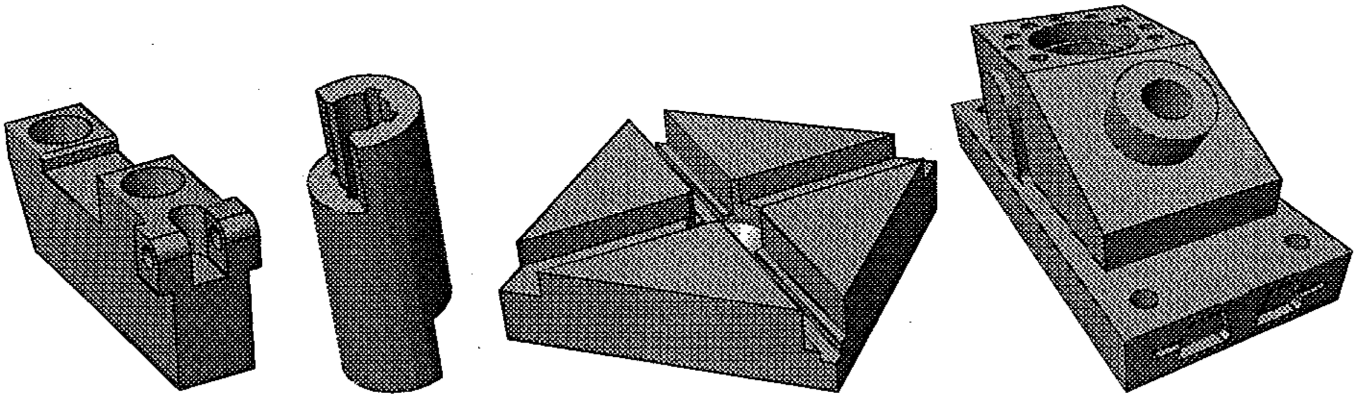


Figure 6: Examples of parts recognized by our procedure.

The reason why Fig. 7 is only a portion of the complete state space is that it shows only those states that result from applying operators to the holes. If we also apply operators to the shoulders (for example, see Fig. 5), we will obtain the complete state space, which contains 32 nodes (four nodes for each node shown in Fig. 7).

PRECEDENCE CONSTRAINTS

The removal volumes in a MRSEV model cannot necessarily be machined in any arbitrary order. Instead, accessibility [22], setup [10] and other types of interactions among them will introduce *precedence constraints* requiring that some of them be machined before or after others.

Let R be a MRSEV model, and let q and r be any two removal volumes in R. We are interested in the following two types of precedence constraints among q and r (we intend to address additional types of precedence constraints in our future work):

1. *Accessibility precedence constraint:* Let a be the accessibility volume for the machining operation used to create r. If $a \cap q \cap W \neq \emptyset$, then this means that the cutting tool approaches r through the volume occupied by q, and thus q must be machined before r. An example is shown in Fig. 8(b), in which the pocket p must be machined before the hole h.

   As we discussed earlier, the removal volume r can be represented as a MRSEV instance. However, the MRSEV library does not include a way to represent the removal accessibility volume a, and thus there is currently no STEP support for identifying accessibility precedence constraints. We discuss this issue further in the Conclusions.

2. *Minimality precedence constraint:* Suppose that machining q before r would create a situation in which it will be possible to machine r using a smaller instance r' of $MRSEV(r)$. Then we constrain r to be machined before q (for otherwise, we would be machining r' rather than r). An example is shown in Fig. 8(c), in which we constrain the hole h to be machined before the pocket p.

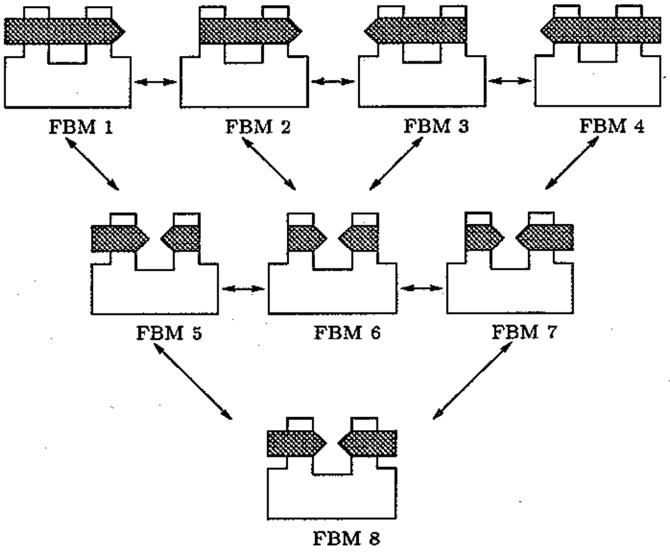
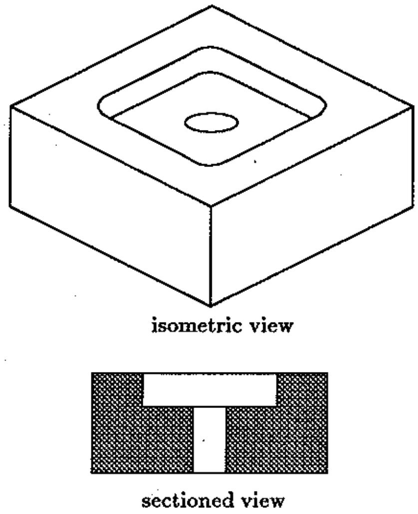


Figure 7: A portion of the state space of MRSEV models for the bracket shown in Fig. 4.

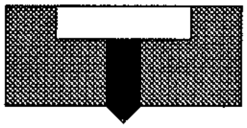
Given a MRSEV model R, a *machining order* for R is any total ordering $\{r_1, r_2, \ldots, r_k\}$ of R that satisfies the precedence constraints.

If there is no machining order for R, then this means that the precedence constraints contradict each other, so that it is not possible to machine R. If there is at least one machining order for R, then we say that R is *machinable*. In this case, the precedence constraints define a partial ordering on the removal volumes in R. We represent this partial ordering using a graph structure called a *time-order graph* (which is essentially identical to a *Hasse diagram* [23]). Fig. 9 shows an example part and its time-order graph.

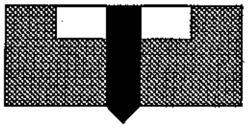
In [8], we present an algorithm called CREATE-TIME-



(a) PART



(b) FBM 1



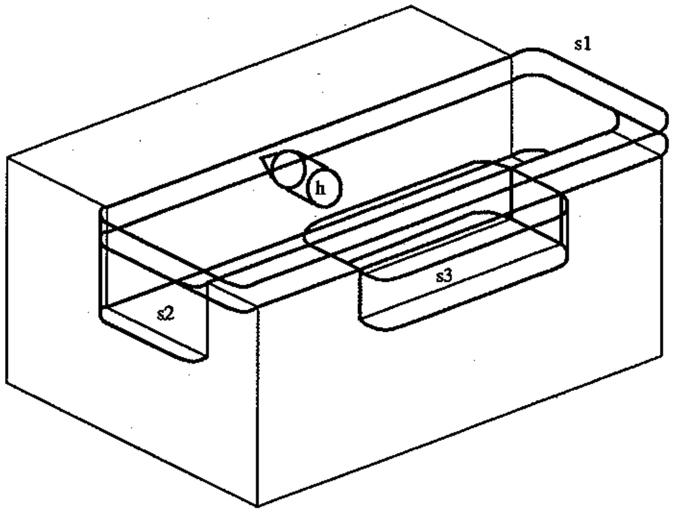
(c) FBM 2

Figure 8: Example of precedence constraints.

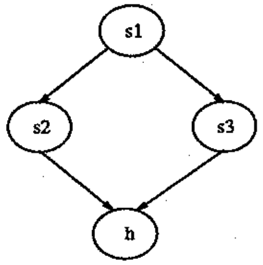
ORDER-GRAPH. This algorithm identifies R's precedence constraints by examining the removal volumes of R and their accessibility volumes, and then it uses these precedence constraints to construct R's time-order graph. Once R's time-order graph has been computed, the set of all machining orders for R is identical to the set of all total orderings consistent with the time-order graph. These machining orders can easily be computed from the time-order graph, using topological sorting techniques [17, 4].

ESTIMATING ACHIEVABLE TOLERANCE

Each machining operation creates a feature which has certain geometric variations compared to its nominal geometry. Designers normally give tolerance specifications on the nominal geometry, to specify how large these variations are allowed to be. Given a candidate operation sequence, the machining data for that sequence, the feature's dimensions, and the material from which the part is to be made, we want to evaluate whether or not it can satisfactorily achieve the tolerance specifications.



(a) part



(b) time-order graph

Figure 9: An example part and its time-order graph.

To get the most accurate results, the best technique is to construct a mathematical model of the machining process. To date, we have done this for turning and boring—and our methodology can easily be extended to model all machining processes involving single-point cutting tools. By modeling the relative motion of the workpiece and the cutting tool, we produce models of topography resulting from the machining process—and from these models, we calculate the achievable tolerances and surface finishes produced by the machining process. Our models take into account the following factors:

1. The machining system parameters, such as the feed rate, cutting speed, depth of cut, and structural dynamics [20, 22].
2. The natural and external variations in the machining process. For example, variations in hardness in the material being machined cause random vibration, which is one of the major factors affecting the surface quality [31, 32, 22].

To model these factors, we use a combination of deterministic, statistical, and empirical techniques [31, 32, 22].

Machining processes that do not involve single-point cutting tools are complex enough that we have not yet succeeded in constructing accurate mathematical models of them. For these machining processes, we are developing empirical models.

ESTIMATING THE COSTS

The total cost of a machining operation consists of two components, the fixed cost and the variable cost. Both of these costs serve as a basis for the economics of machining operation planning. The fixed cost mainly consists of depreciation of machining equipment, maintenance disbursements, and administrative expenses. The variable cost consists of the costs which vary in accordance with the level of production activity. Typical examples of variable cost would be the cost related to the machining activities, tooling, and auxiliary activities. Note that the fixed cost is the part of the total cost which remains at a constant level even when different operation sequences are used.

The methodology for estimating the fixed and variable costs of machining operations is well understood; formulas for estimating these costs can be found in standard handbooks. The particular formulas we use are presented in [30, 22].

IMPROVING COMPUTATIONAL EFFICIENCY

Given a MRSEV model R, we will want not only to generate other interpretations equivalent to R, but also to generate their time-order graphs. One approach for this task is to use a state-space search to generate alternative MRSEV models as illustrated in Fig. 7, and then use the CREATE-TIME-ORDER-GRAPH algorithm to produce the associated time-order graphs. However, such an approach would be very expensive computationally, because of the repeated calls to CREATE-TIME-ORDER-GRAPH.

A much more efficient approach can be devised by noting that given a MRSEV model R and its time-order graph, if we apply a reinterpretation operator to produce an alternative MRSEV model R', we can produce R''s time-order graph at the same time, by making some simple changes to R's time-order graph. In [8] we describe how to augment the reinterpretation operators to accomplish this.

We can improve the efficiency even further by noting that it is not necessary to examine every one of the MRSEV models for P and S in order to find the best ones. Instead, we can use heuristic techniques to discard unpromising MRSEV models, and examine only the promising ones. The basic idea consists of the following loop [9]:

1. Use reinterpretation operators to generate a new MRSEV model R of P and S.
2. Map each of R's removal volumes to the machining operation(s) capable of creating it. Augment R to include the accessibility volumes corresponding to these machining operations. Identify the precedence constraints, and use them to construct R's time-order graph.
3. Use mathematical and empirical models to determine the time and cost of each machining operation, and the machining tolerances and surface finishes it can produce. If any of the operations cannot achieve the required tolerances and surface finishes, then discard R. Otherwise, compare R against the MRSEV models seen previously, retaining only the ones that look the best.
4. If there is reason to believe that no other MRSEV model is significantly better than the ones we have seen so far, then exit, returning the best MRSEV models we have found, along with their time-order graphs. Otherwise, go to Step 1.

Some of the details of this procedure have still not yet been fully developed. For example, the procedure needs a time-out feature: even if there is no reason to believe there isn't a better MRSEV model, it should stop computing after a while. The further development of this procedure is a topic for future work.

STEP SUPPORT

If there were standard, widely available ways to represent the removal volumes and accessibility volumes associated with machining operations, this would increase the potential impact of our work tremendously, by enabling us to develop modules that could easily be interfaced to any CAD/CAM systems that use those representations. Thus, we are interested in how STEP might be used to provide representation schemes for removal volumes and accessibility volumes. In this regard, we note the following:

- To represent removal volumes, we can use Kramer's library of MRSEVs (Material Removal Shape Element Volumes) [18, 19], which can be defined formally using a combination of EXPRESS (the STEP information modeling language) and STEP form features. Kramer has defined a portion of the MRSEV library formally in this manner, and has defined the rest of it using an EXPRESS-like language. This MRSEV library only represents the removal volumes produced by 3-axis machine tools, but it should be possible to extend the library to cover additional kinds of machining operations.
- No similar STEP library of machining accessibility volumes has yet been developed, so it is not yet possible to provide a complete implementation of our approach based on STEP. However, it should be possible to develop such a library.

We are interested in the possibility of extending the MRSEV library to cover additional kinds of machining operations, and developing a similar STEP library of machining access volumes. Not only would this be useful for our research program—but since many important issues in the manufacture of machined parts depend on the removal and accessibility volumes produced by machining operations, we believe it would be useful for computer-aided design and manufacturing in general.

FUTURE WORK

Generating Redundant MRSEVs

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 and (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 procedure described in the draft does not allow redundant MRSEVs at any point. The redundant MRSEVs should certainly be generated before a cutting order is established and cost is estimated. (If we are drilling and boring a dozen similar holes in a workpiece, the lowest cost order is to drill them all then bore them all, for example).

Alternative MRSEVs for Different-Sized Tools

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

1. If we are 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.
2. If a large pocket contains tight corners into which a large tool will not fit, a large MRSEV should be generated in which the tight corners are rounded, and each tight corner should have its own small MRSEV. A small tool should be used for the large MRSEV and small tools for the small MRSEVs.
3. If a MRSEV is defined for removing some delta volume, in some cases the corners of the MRSEV may have radii assigned to them arbitrarily. All of the MRSEVs for cutting the shoulders of the part in Figure 5 of the draft are examples of this. A smaller radius lets a smaller MRSEV be defined (which helps avoid interferences) but requires a small tool, while a larger radius allows a larger tool to be used. Some heuristic rules are needed to determine radii when generating a MRSEV model.

Setups

Our current approach does not deal with the machinability considerations involved with setting up the machine tool in order to perform the machining operations. Addressing this issue is a major problem for future work.

CONCLUSIONS

In this paper, we have outlined our approach for generating and evaluating alternative operation sequences for machined parts. The primary goals of our work are as follows:

1. Pushing process engineering upstream, by providing information about the machinability of the design. We hope this information can help designers modify the design if necessary to balance the need for efficient machining against the need for a quality product.
2. Providing information about alternative ways in which the part might be machined. We hope this information will aid process engineers or process planning systems in developing alternative process plans, so that the most appropriate plan can be selected depending upon machine tool availability and/or other constraints specific to plant facilities.

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