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PROCESS PLANNER'S ASSISTANT: AN INTERACTIVE AND ITERATIVE APPROACH TO AUTOMATING PROCESS PLANNING

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ABSTRACT

Most existing approaches to computer aided process planning aim for full automation by searching for a plan that is optimal with respect to a pre-specified objective function. Such full automation is often infeasible in practice for three reasons: (i) the search space of potential plans is huge, (ii) optimality metrics are often context sensitive and can only be elicited through user interaction, (iii) because of the importance of process planning, organizations are more interested in process planning assistants that support human expert process planners rather than stand-alone process planners.

In this paper, we present a "process planner's assistant", which *helps* the human process planning experts in coming up with process plans. In order to achieve this, the process planner's assistant must have access to the full search space of process plans, and the ability to modify plans in response to human criticism. The former is provided by basing our system on ASU Features Testbed, a comprehensive and systematic framework for recognizing and reasoning with features in machinable parts. To support the latter, the system is equipped with an incremental and interactive search mechanism. We will discuss the operational details of the resultant system, called ASUPPA.

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1 INTRODUCTION

Computer aided process planning (CAPP) is a key part of bridging the link between design and manufacturing. Process planning involves determining the sequence of operations to perform to manufacture a part given its description and the specification of the resources in the workshop. It should take into account both technological and economic considerations, some of which are hard constraints and some preferences. This knowledge often represents both the experience and the know-how of engineers/specialists, which differ from one company to another.

Most existing approaches to CAPP (Britanik,1995; Gupta,1994; Hayes,1996; Kambhampati,1993) aim for full automation by searching for a plan that is optimal with respect to a pre-specified objective function. Such approaches suffer from three important limitations.

- The search space for process plans is too large to facilitate an efficient systematic search. This often necessitates restricting focus to a single interpretation of current design and finding the best plan under this fixed feature set (which may not be the best plan globally).
- Second, and perhaps more important, these approaches assume the availability of a pre-specified objective function for evaluating process plans. In reality, the eval-

uation metrics for process plans are very much context dependent, and it is rarely the case that an accurate optimality metric is available *a priori*. Trade-offs among optimization objectives typically reflect user preferences and the presence of additional domain constraints not captured in the planning model. Moreover, the user may change the optimality criteria for the process planning during the process of finding an optimal solution. Since the optimality metric is not completely known, we would like to take the user/process planning expert to be the final arbiter on the quality of the plan produced. Accordingly, if the expert is not satisfied, the planner should be able to resume its search for an improved process plan.
- A third and related shortfall of the current approaches is that they attempt at full automation in a situation where organizations are not comfortable delegating full process planning responsibilities to a computer.[2]

In this paper, we present a framework called ASUPPA that can act as a "process planner's assistant" to human process planning experts. In order to provide sound and effective assistance, ASUPPA must be able to function in a quasi-independent status, depending on the user for only an occasional critique (since otherwise, the human expert will be forced to do all the planning). This implies that the planner must have deep knowledge about process plans, including having access to the full search space of process plans; and the ability to modify plans in response to human criticism. The former is provided by basing it on ASU Features Testbed (ASUFTB), a comprehensive and systematic framework for recognizing and reasoning with features in machinable parts. To support plan modification, the system is equipped with an incremental and interactive search mechanism.

The task level architecture of ASUPPA is shown in Figure 1. The intended user is an experienced human process planner, who is knowledgeable both about the products and about the manufacturing facilities of the factory. The planner starts with a default plan generated by ASU Features Test Bed, and examines and improves it incrementally. The modification is guided by default quality criteria which can be changed through the interaction with the user and the feedback given by evaluation module and user. Once the planner reaches a local minimum with respect to its current objective function, the criticism is requested from the user. If the user is satisfied with the current plan he may

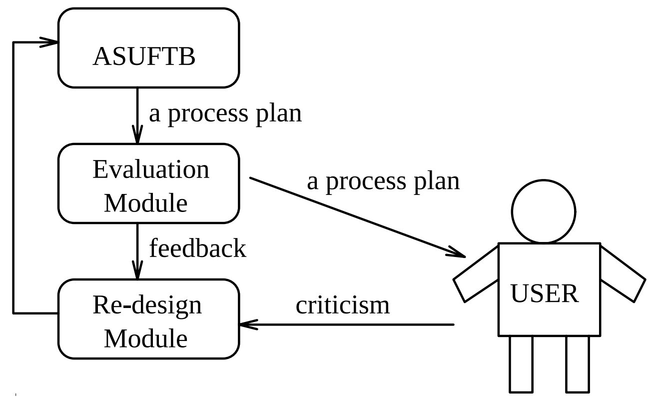

Figure 1. THE ARCHITECTURE OF PPA

terminate the process; else he will criticize the plan. The criticism is incorporated into the current plan, which is then made the new seed plan and the process continues. This approach is advantageous in that the interaction with the user is done infrequently and is used only to validate a process plan or criticize the plan.

Conceptually, we can see ASUPPA as navigating the search space that is set up by ASUFTB, aided by its evaluation module and user criticism. In order to implement this approach, we need to structure the interaction between the planner and the user, and also determine the details of the planner's iterative search process. In particular, we need to answer the following questions: (a) how is the search space of potential process plans represented? (b) how are plans evaluated? (c) how is the interaction with the user structured? and (d) how are plans revised on the basis of evaluation or user feedback? We will address these issues in the following sections with the help of an example.

The rest of this paper is organized as follows. Section 2 briefly reviews the ASUFTB, and the representation of process plans within it. Section 3 discusses the architecture of our PPA – concentrating on how plans are evaluated both by PPA and by the expert user, and how they are modified in response to the evaluation. Section 4 describes related work and section 5 gives the conclusions and the future work.

2 THE ASU FEATURES TEST BED (ASUFTB)

As mentioned earlier, ASUPPA's knowledge about process plans is derived from the ASU Features Test Bed (ASUFTB), which is developed by Shah et al. (Shah,1994). ASUFTB can systematically enumerate alternative features and machining interpretations for an object and these interpretations can be used to systematically enumerate all candidate machining plans.

We will now briefly describe the operation of ASUFTB

[2]Prof. Mantyla, a prominent process planning researcher, relates an anecdote about how when his research group offered their state-of-the art process planning system for use in a Finnish company, the company politely refused saying that process planning is too important an activity to be entrusted solely to a program.

name	*symbol description*
P	Part
S	Stock
R	Removal volume S-P
a	Atomic cell
A	Set of all the atomic cells identified for R
c	Composition of some atomic cells (c $\subset$ A) If two cells need to combine, they should share a common surface. Any number of cells which satisfy this property can be combined into one composite cell. Direction of combination is always perpendicular to this surface
C	Set of all composite cells
m	Machining operation, an instantiation of a template machining operation. All the parameters are known at this instant
f	Feature based model (FBM)
F	Set of all FBMs (f)
ms	Machining sequence, an ordered list of composite cells $\langle c_i, c_j, c_k, \ldots\rangle$
mp	Machining process, an ordered list of machining operations $\langle m_i, m_j, m_k, \ldots\rangle$
wp	Represents the process plan. It is a tuple consisting of the following elements. $\wp = \langle$ A, mapping from A $\rightarrow$ C, mapping/ordering from c $\rightarrow$ f, mapping from f $\rightarrow$ ms $\rangle$

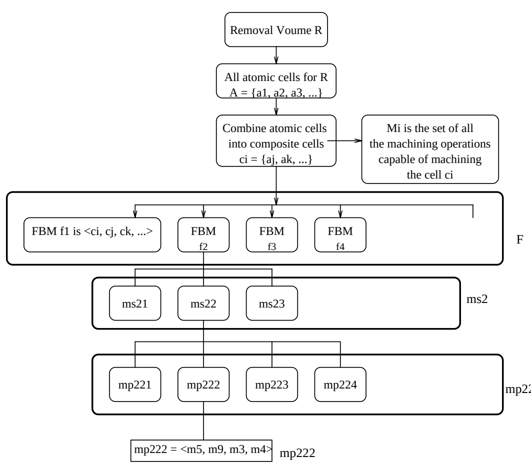

Figure 2. SYMBOLS USED FOR EXPLAINING THE MATHEMATICAL REPRESENTATION OF ASUFTB. ON THE BOTTOM THEY ARE REPRESENTED IN A TREE FORM

with the help of the notation in Figure 2 and the example in Figures 3, 4, 5 and 6. [3]

[3] We use a simple example for ease of exposition.

ASUFTB is a design by feature system and uses the following approach to recognize all possible interpretations and machining features in a given part. First, the total volume to be removed by machining, called as total removable

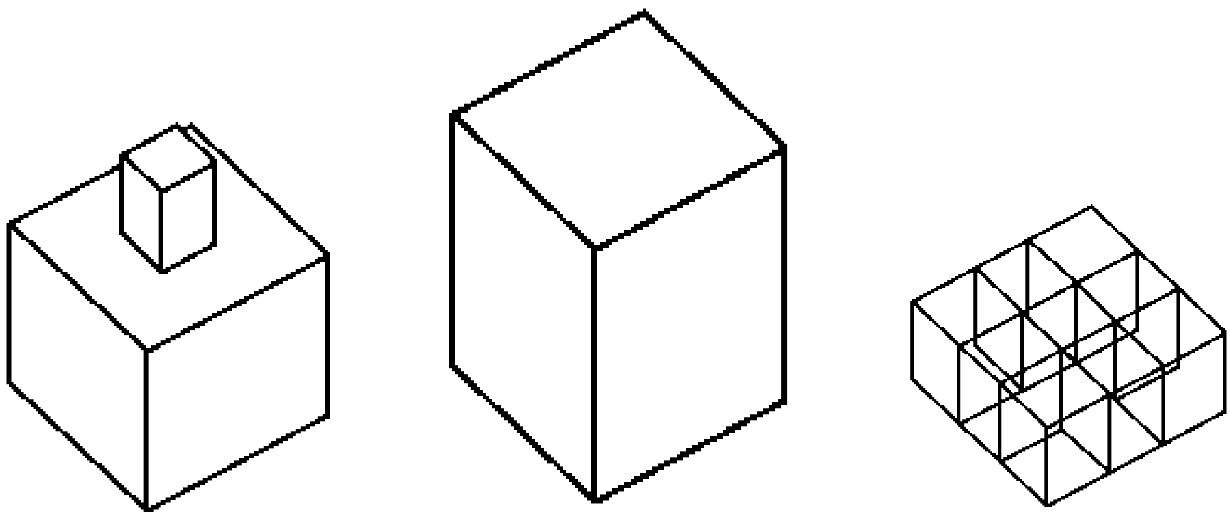

Figure 3. EXAMPLE: PART (P) AND STOCK (S), THE REMOVAL VOLUME R (S-P) IS DECOMPOSED (USING HALFSPACE PARTITIONING) INTO 8 ATOMIC CELLS

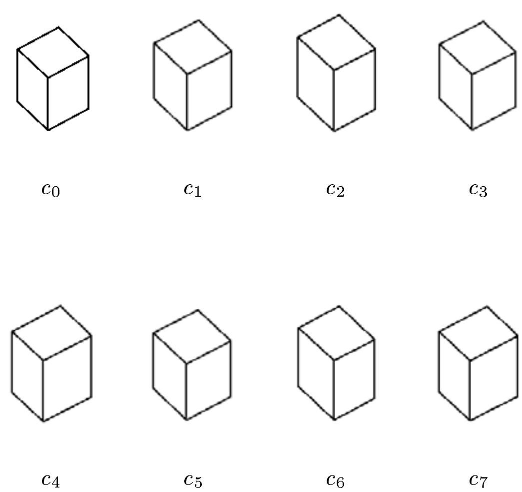

Figure 4. ATOMIC CELLS FOR THE REMOVAL VOLUME R (c_0 to c_7)

volume (R) is obtained by subtracting the part (P) from the stock (S). Second, the total removal volume R is decomposed into minimum convex cells called atomic cells using a method called halfspace partitioning (Shah,1994)(refer to Figure 3). A plane cuts the space into two half spaces. Half space can thus be fully characterized with a plane and a direction associated with its normal. All points in space which lie in the direction of this normal are said to be on the positive side of the halfspace and all the other points are said to be on the negative side of the halfspace.

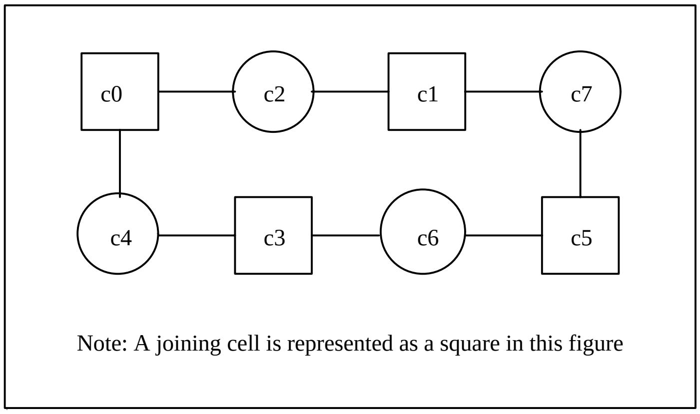

Figure 5. CELL ADJACENCY GRAPH (CAG) FOR THE REMOVAL VOLUME

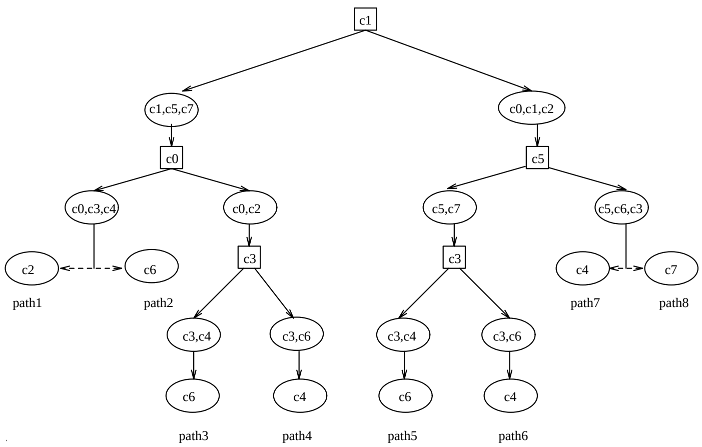

Figure 6. ONE MACHINING SEQUENCE TREE (MST) OBTAINED FROM THE CELL ADJACENCY GRAPH (CAG) SHOWN IN THE PREVIOUS FIGURE. SQUARE NODES IN THE TREE STAND FOR JOINING CELLS. CELLS IN ONE OVAL ARE COMPOSED INTO A COMPOSITE CELL. A PATH FROM A ROOT TO A LEAF DEFINES ONE MACHINING SEQUENCE. COMPOSITE CELLS ARE REMOVED IN TOP DOWN ORDER. COMPOSITE CELLS CONNECTED BY DASHED LINES (IN THE SEQUENCE TREE) CAN BE MACHINED IN ANY ORDER, AS LONG AS THEIR PARENT IS MACHINED FIRST.

Suppose we need m half spaces $H_1, H_2, \ldots, H_m$ then every atomic cell produced by halfspace partitioning is assigned a m dimensional vector called a *halfspace vector* (HSV). $HSV = \langle d_1, d_2, d_3, \ldots, d_m \rangle$, where component d_1 corresponds to H_1, d_2 to H_2 and so on; d_i is 1 or 0, where 1/0 means the lump lies in the positive/negative half of the corresponding halfspace. Figure 4 illustrates eight minimum convex cells decomposing from R using halfspace partitioning method.

The HSVs are used to generate a graph called *cell adjacency graph* (CAG) and an example of this graph for the atomic cells in Figure 4 is shown in Figure 5. The nodes in CAG represent atomic cells and arcs represent adjacencies. Two cells are considered to be adjacent if they share a face on the same half space. Note that two atomic cells are adjacent iff they lie in the *same* side of *all* halfspaces *except one*. Some atomic cells, represented as rectangles in Figure 5 need special consideration as these cells serve as crossroads and they signify there exist alternative ways of composition. Those special cells are called *joining cells*.

Because most discrete machining processes produce non-concave removal volumes as much as possible in a single setup, the composite cells to be removed in a single setup should be maximally convex. A machining sequence is an ordered list of composite cells by which the removable volume R can be removed. Machining sequences are generated from the CAG. The procedure starts at a joining cell. Adjacent cells are continuously concatenated unless the volume becomes concave. At this stage the concatenated volume is maximally convex and is assumed to be machinable, so it is removed from the CAG and the process begins again at some other joining cells. This process yields alternative trees called *machining sequence trees* (MST). If the original removable volume has n joining cells, the result of the composition will generate n MSTs since this procedure can start at any joining cell. Four MSTs can be generated from the CAG in Figure 5. One of them is shown in Figure 6. Square nodes in the tree stand for joining cells. Cells in one oval are composed into a composite cell. A path from a root to a leaf defines one machining sequence. FBM is a collection of composite cells whereas a machining sequence is an ordered list of composite cells and so there can be more than a machining sequence for a given FBM.

Every machining sequence is an input to the process selector where process selection is done for individual features(composite cells) in the sequence on the basis of shape capability of the process (Shirur,1994). A machining expression based on type of tool-workpiece interaction and tool motion characteristics is generated for each feature. Machining processes in ASUFTB are modelled in terms of constraints on the tool shapes, cutting motion types between the tool and the workpiece, and possible directions of feed motion. Feasible process for each feature is determined by matching their process constraints with machining expression of this feature. Any process whose constraints completely match the terms in the machining expression is added to the list of feasible processes for a given feature. Since a feature can have multiple machining expressions and each of them maps to several alternative processes, an exhaustive list of alternative processes for each machining feature is generated.

In summary, support for process planning in ASUFTB comes at three different levels. First called the "cell level" involves splitting the removal volume into atomic cells and combining them into MSTs. Second called the "sequence level" involves picking a FBM corresponding to a specific traversal of the MSTs. Third, called the "process level" involves picking feasible machining processes for each of the features in the chosen FBM. Thus, ASUFTB implicitly sets up the search space consisting of all potential machining plans(sans setup considerations) for machining the part. The role of ASUPPA is to navigate this search space guided by the evaluation metrics and the user feedback.

3 ARCHITECTURE OF ASUPPA

In this section, we will describe how plans are evaluated, how the interaction with the user is structured and how the plans are modified iteratively in response to the feedback coming from evaluation module or user criticism. The system can be considered as consisting of two loops, internal loop and external loop (see Figure 8). The internal loop aims to find a local optimal plan with respect to the default criteria in the planning system. The external loop will take the output of the internal loop, and the user's feedback to find a process plan that satisfies the user. Therefore, the process planning system becomes a semi-automatic system and the user and the evaluation module will steer the planner from case to case.

3.1 Plan Evaluation

First, we explain how a plan is evaluated and what kind of feedback is given after the evaluation. A plan is evaluated from two levels: sequence level and process level. The feedback information will help in re-designing plan afterwards. There are three sequence level evaluation operators: accuracy, consistency and operation time. Accuracy at sequence level measures the ability of process plans to produce the nominal geometry. Its feedback is a textual one which lists the identities of all misplaced features (note the feature ids are unique for every feature in the entire space of alternative feature compositions). Consistency operator measures the ability of process plans to repetitively produce the part within the specified tolerances. Operation time operator will evaluate the following aspects of operation time: (i) Air time, when no cutting is done but the tool is being moved from one position to another; (ii) Tool change time, which depends on the number of types of features. The feedback from either consistency operator or operation time operator is a value indicating the deviation from the specified one.

In process level evaluation, feasibility, accuracy, consistency, and operation time are used as evaluation parameters. This evaluation level looks at how good a process is to produce the individual feature. Although accuracy, consistency and operation time have the same name as they have in sequence level evaluation, the focus is different. Accuracy at process level checks whether the assigned processes meet the form and finish specifications. A textual feedback is given indicating the names of the satisfied form or finish specifications and their deviation values (goodness values), and names of the unsatisfied specifications and their deviation values (badness values). Consistency at process level focuses on the repetitive capability of processes to produce intrinsic dimensions of a feature within the specified tolerances. The names and deviation values of the satisfied and unsatisfied tolerances are also given in the feedback. Operation time at process level considers only machining time which is the amount of time taken for removing the feature volume by the machining process. The numerical value of the machining time and its deviation value (how close it is to the specified one) are returned as a feedback. In feasibilty evaluation operator, the size capabilities of processes are compared with the intrinsic dimensions of features and checked whether they are feasible candidates for machining the feature volume. The feedback is also a textual one which indicates the types of the constraints that are not satisfied and the associated deviation values (badness value).

Example: Let us illustrate the operation of the evaluation module with the help of the following example. Suppose the process to be evaluated is plunge milling. The feature to be generated by this process is a cylinder. Its diameter is 10 inches. The specified tolerance for the diameter is 0.1 inch. Let us say the planner is now trying to evaluate consistency of plunge milling process at the process level. From the above discussion, we know that the consistency evaluator at the process level checks whether the intrinsic tolerance (in this case, the intrinsic tolerance is diameter tolerance) can be achieved by the process at hand (now the process is plunge milling). In ASUFTB, the tolerance capabilities of processes are represented in the process definition files. An excerpt of the tolerance capability representation for plunge milling process is as follows:

Distance Line e1 Line $e2 > 1$ 0.01

Distance Line e1 Line $e2 < 20$ 0.01

where e1 and e2 are two parallel lines in plunge milling tool profile. 1 and 20 are the minimal diameter and the maximal diameter, respectively, required by the plunge milling process. 0.01 is a value indicating the percentage of the nominal dimension and it is the amount of plunge milling process variation. Here, the total process variation is the product of the percentage value and the diameter of the feature. That is, for current plunge milling process, the variation is 10*0.01=0.1, which satisfies the requirement of diameter tolerance. The deviation value for diameter tolerance of plunge milling process is calculated using the following formula :

Deviation = (tolerance - %value * nominal dimension)/tolerance

In this case, the deviation value is 0. It indicates current process (plunge milling) can guarantee the specified tolerance (0.1). The feedback given by consistency evaluation operator is diameter tolerance (name of the satisfied tolerance) and 0 (deviation value). If the deviation value is negative, it implies that the evaluation parameter is not satisfied. Re-design module will try to modify the plan in response to the unsatisfied one (see Section 3.3 below).

More details about the implementation issues of these evaluation operators and their feedback can be found in (Hirode,1996).

3.2 The role of user expert

After plan evaluation, the next question which needs to be addressed is "*How is the interaction with the user structured?* ". When the plan given by the planner is provided to the user, an information editor is poped up at the same time. The editor displays the evaluation operators used in process planner, the weights assigned to each of them and the machining time evaluation for each feature. If the user is satisfied with current plan the algorithm terminates. If the user criticizes the plan by changing the weights, a new process plan consistent with the new objective function is generated through the planner. If the user is not satisfied with the machining time of one feature, a modification method is used to generate new features and the planning system will find a FBM without the bad feature and including not only new generated features but also as many old good features as possible. Figure 7 is an example of information editor. The number corresponding to an evaluation operator is the weightage assigned by default. The number corresponding to a feature is its machining time (unit is minute). If the user is not satisfied with current plan, she can either change the value of weightage to a new one, or point the feature which she doesn't like. The planner will incorporate her criticism and find a new plan which satisfies his requirement through plan modification.

3.3 Plan Modification

In previous sections, we discussed how a plan is evaluated and how the interaction with the user expert is structured. Now it is time for us to answer the question "*how should the plan be modified using the feedback given by evaluation module or the user?* ". In this section, we will describe the modification methods used in ASUPPA in detail.

ASUPPA attempts to improve the current plan from three levels: *process level, sequence level and cell level.* In process level, the planner uses the same FBM, but replaces some of the existing machining operations with different ones. This corresponds to changing the mappings from composite cells to machining operations. In sequence level, the planner uses a different FBM with the same feature set as the current one but a different order, and starts looking for the best plan for this FBM. This corresponds to changing the order of features in current plan and may not result in the reordering of machining operations. In the cell level, the planner modifies the existing FBM incrementally so that it results in a better plan. The planner just disregards all the mappings for features which are no longer present in the new FBM and adds those mappings/features which were not present in the previous FBM. This method can be considered as a splitting and merging of the composite cells in the FBM. This will result in a different FBM, which avoids the offending feature that necessitated replanning but keeps as many of the rest of the old features as possible.

The flow chart for plan modification is shown in Figure 8. We will illustrate it with the previous example to show the details of the cell level modification method.

Activities	Weightage./Machining Time	New Value
Feasibility	10	
Accuracy	7	
Consistency	7	
Operation time	5	
Feature 1	15	
Feature 2	12	
Feature 3	8	
Feature 4	11	
Feature 5	5	
Feature 6	7	

O.K CANCEL

Figure 7. INFORMATION EDITOR

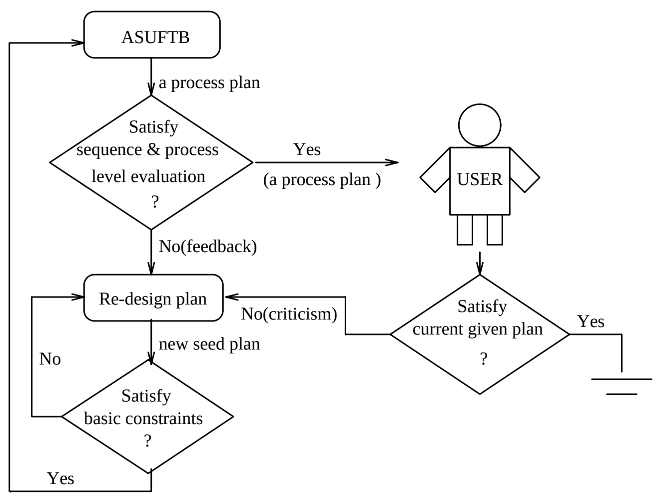

Figure 8. FLOWCHART OF ITERATIVE AND INTERACTIVE PLANNING ALGORITHM : STARTS WITH A DEFAULT SEED PLAN AND GENERATES LOCAL REPAIRS BASED ON THE CURRENT OPTIMALITY CRITERIA. APPLY THE MOST PROMISING OF THESE REPAIRS AND SHOW IT TO USER. IF THE USER IS NOT SATISFIED WITH THE CURRENT PLAN HE WOULD CRITICIZE IT AND HIS CRITICISM IS INCORPORATED INTO THE CURRENT PLAN. THE CURRENT PLAN IS THEN MADE THE NEW SEED PLAN AND IT GOES THROUGH THE ENTIRE CYCLE AGAIN

Let the current FBM be

$$f = \langle \{c_1, c_5, c_7\}, \{c_3, c_6\}, \{c_0, c_4\}, \{c_2\} \rangle$$

(see Figure 4 for atomic cell information). Figure 9 shows these features in their machining order (left to right, top to bottom). The machining time for the first feature is large when compared to the other features. Suppose that when the user sees the features' machining time, he rates the first as bad. The planner incorporates this criticism into current plan and then begins to improve the machining time for the first feature. Since the machining time is proportional to the amount of material being removed and has nothing to do with the feature or operation orderings, the planner has to try to do split and merge to reduce the amount of material being removed. The planner starts with f and it tries to pick up a joining cell from the feature $\{c_1, c_5, c_7\}$ and merge it with any of the other features, in this case the joining cell picked up is c_1 and the selected feature is $\{c_2\}$. They can combine since c_2 and c_1 share a surface. This is the splitting stage of this operation. At the end of this stage, we have $\langle \{c_5, c_7\}, c_1, \{c_3, c_6\}, \{c_0, c_4\}, \{c_2\} \rangle$.

After combination, a new composite cell $\{c_1, c_2\}$ is generated. Then the planner checks this composite cell and

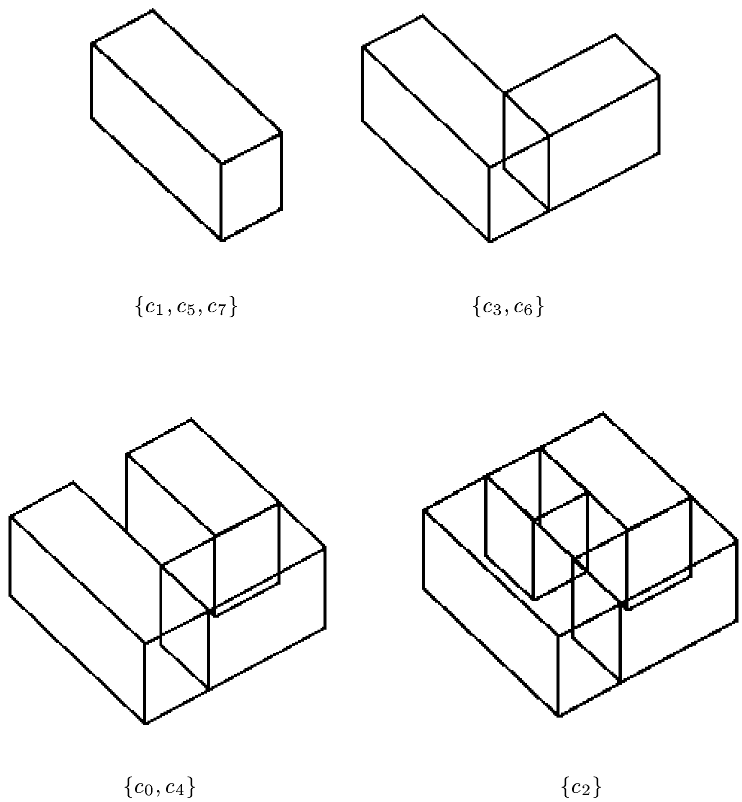

Figure 9. ILLUSTRATING CELL-LEVEL MODIFICATION OF PLANS. FIGURE SHOWS HOW THE FEATURES COMPRISING THE FBM ARE REMOVED ONE BY ONE STARTING AT THE TOP LEFT. THE ATOMIC CELLS CORRESPONDING TO EACH REMOVED FEATURE ARE LABELLED UNDER THE RESPECTIVE SUBFIGURES

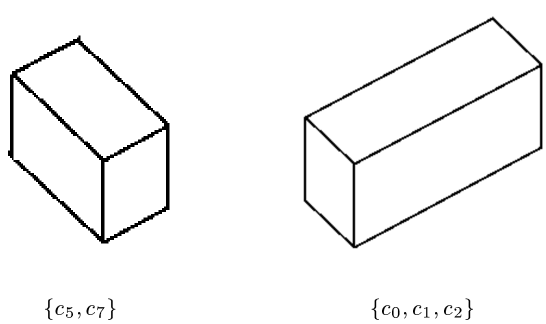

Figure 10. ILLUSTRATING CELL-LEVEL PLAN MODIFICATION. NEW GENERATED FEATURES AFTER APPLYING SPLIT-AND-MERGE METHOD TO THE FIRST FEATURE IN THE PREVIOUS PLAN

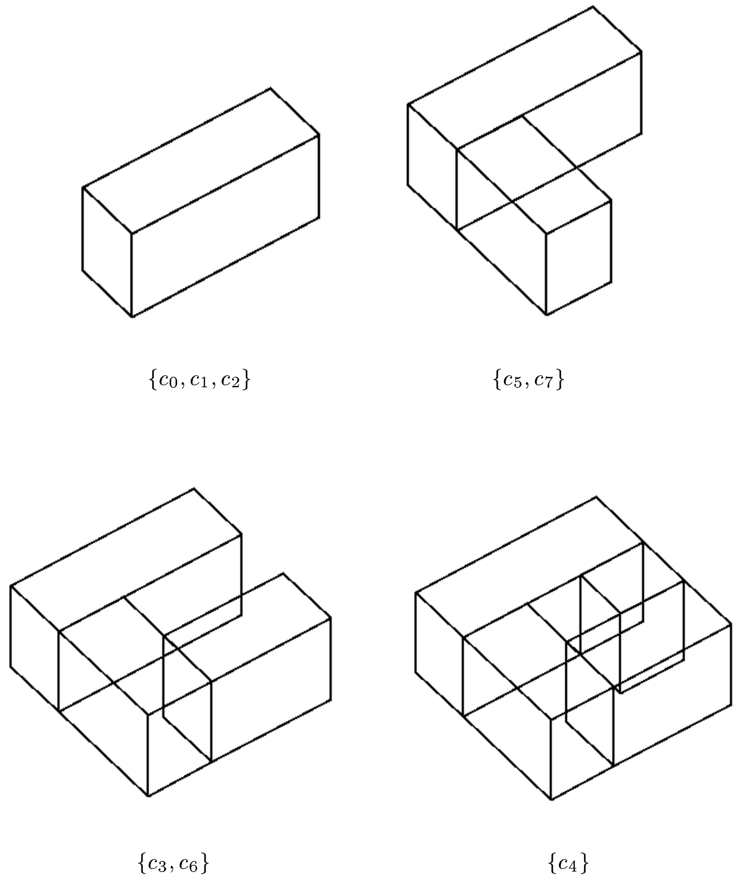

Figure 11. ILLUSTRATING CELL-LEVEL MODIFICATION OF A PROCESS PLAN. FIGURE SHOWS THE ORDER IN WHICH FEATURES COMPRISING THE NEW FBM ARE REMOVED DURING MACHINING. THE ATOMIC CELLS CORRESPONDING TO EACH REMOVED FEATURE ARE LABELLED UNDER THE RESPECTIVE SUBFIGURE

finds that it is not maximum convex (recall that we focus on maximally convex features),and can combine with c_0. The planner does the merge operation again and generates a new feature $\{c_0, c_1, c_2\}$. Thus, the resulting new generated machining features are $\{c_5, c_7\}$ and $\{c_0, c_1, c_2\}$ (see Figure 10). The new FBM should not only include these two new features, but also include as many old features as possible. The planner uses this heuristic information and goes to the search space to find the required FBM. Recall that all the FBMs can be generated by traversing the MST (Figure 6). Figure 11 shows the features (in their machining order) as found by the planner to be included in the required FBM (displayed from left to right, top to bottom).

3.3.1 Managing Changes During Modification.

When the planner modifies a plan at any of three levels, the tweaks can affect all the evaluation parameters. The magnitude of the effect on each parameter will differ from case to case. In order to guarantee that the new generated plan will have more possibility to pass through the evaluation procedure and thus enhance the efficiency of planning, it is checked first using some basic constraints before it goes into the evaluation module. The plans which violate the basic machining practice will be pruned and do not have to pass through the evaluation module. There are two basic constraints: feature precendence constraints and set up constraints. To guarantee the accuracy of a machining sequence, reference feature should be machined before the features that are referenced with respect to it. Moreover, features closer to the reference should be machined before those that are farther. Feature precedence constraints are used to check these two situations and can be set up by retrieving the dimension graph of the given part and its workpiece and calculating the distance between the feature and its reference. The dimension graph is a two dimensional array which is built when the tolerances are given to the part and the workpiece. It records the features, their references and the required tolerance values.

Since most of the manufacturing cost depends much on the set up cost, we have to consider some basic constraints on setups of the plan to prune unpromising plans as early as possible so that the search space can be reduced a lot and find an optimal plan efficiently. Two aspects of setup planning are of prime concerns in process planning: number of setups and quality of setups. Number of setups directly affects the total setup time which is a big part of the total operation time. The number of setups required to machine the part is determined primarily by the approach direction of the features and the precendence constraints among them. It also depends on the number of feature types classified based on shapes and tolerance specifications. Using the method described by Das, Gupta and Nau(Das,1994), the minimum number of setups can be estimated and the plan whose number of setups are less than that number will be pruned immediately because of its impossibility.

After above checking, the plan which satisfies the basic constraints will be sent into the evaluation procedure and continues the iterative and interactive process. Otherwise, the planner will remodify the previous plan to make sure the new generated plan be better.

3.4 Status of Implementation

We have implemented the evaluation module, split-merge method (cell level modification method) and the interface which allows user to change the evaluation parameters (part of Figure 7). The example given in the paper has been successfully run in ASUPPA. We also tested our approach using the more complex example shown in Figure 12.

4 RELATED WORK

ASUPPA system builds on, and is thus related to, several previous process planning systems. The iterative operation of ASUPPA is closely related to the "iterative redesign" used in the DOMINIC system (Dixon,1986). The differences stem mainly from the rich structure of process plans in ASUFTB/ASUPPA as compared to the parametric designs that are improved in DOMINIC. This makes the "modification" of plans considerably more involved in ASUPPA. The importance of replanning in process planning has been recognized in systems such as Nextcut (Kambhampati,1993). A difference is that while systems such as Nextcut are best seen as assistants that offer process planning advice to designers, ASUPPA should be seen as an assistant to expert process planners. Another difference between ASUPPA and the Nextcut process planning system is that ASUPPA is based on a more systematic feature interpretation framework. ASUPPA is also closely related to the IMACS system (Gupta,1994). The primary difference is that while IMACS is intended to be a stand-alone process planner, ASUPPA is designed to be a process planner's assistant. Accordingly, IMACS is driven by a multi-level branch and bound search that seeks to find a plan that is optimal with respect to a pre-specified optimality metric, while ASUPPA is driven by an iterative improvement search that aims to find a plan that satisfies the internal and external (user) evaluation. Both systems are based on first principles substrates that support enumerating and handling multiple interpretations of the given part.

5 CONCLUSIONS AND FUTURE WORK

In this paper, we argued that automation of process planning is best done through interactive process planning assistants that can handle shifting optimality criteria rather than stand-alone process planning systems with pre-specified objective functions. We proposed an architecture – ASUPPA – that assists an expert process planner. We described and illustrated the implementation and operation of ASUPPA on top of the ASU features testbed, concentrating in particular on how a plan is evaluated, how the interaction with the user is structured and how a plan is modified using the feedback provided by the evaluation module or the user criticism. Features considered here are basically linearly or rotationally swept volumes usually produced on a 3-axis machining center. The surface types included right now are planner, cylindrical and conical. We believe that this type of process planning approach can provide the right balance between completely automated vs. user-assisted process planning. Future work will focus on handling the interactions between the factors affecting the goodness of processes and features. The factors are described using constraints. The interactions between these factors will finally be reflected by a cost which is obtained by calculating the penality of all violated constraints while improving the plan. Getting an optimal plan will correspond to minimize the cost.

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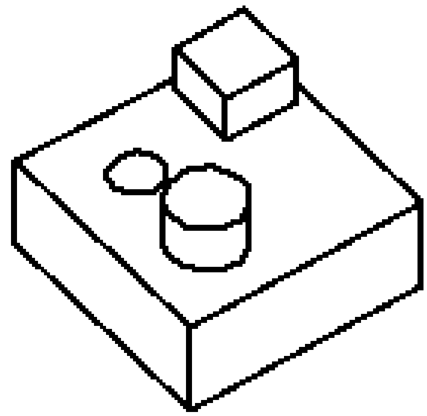

Figure 12. EXAMPLE PART 2

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