Planning for the manufacture of axisymmetric parts: an AI-based approach
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1 Introduction

The interest in automated process planning in recent years reflects its intellectual challenge and points to the economic potential of its widespread use. Systematizing the generation of process plans is critical to achieving a higher efficiency and consistency of manufacture. This paper deals with the automation of process planning for machined components. We are interested in synthesizing detailed and efficient plans which will relieve the planner from routine tasks so that he can perform more interesting and challenging jobs. Our objective is twofold: to generate process plans for routine parts quickly and efficiently, and to satisfy the specifications of tight tolerances, both dimensional and relative, for high-precision parts. The overall intent is to study the issues associated with the representation of knowledge, its acquisition and application as they pertain to the synthesis of process plans.

Efforts directed toward developing automated process planning systems [1] have followed either of two approaches: Variant and Generative.

The Variant approach is characterized by an efficient system for storing and retrieving plans. It incorporates elaborate classification schemes using Group Technology (GT) concepts. Parts for which plans need to be found are assigned a GT code (a long string of alphanumeric characters) based on their geometric and technological characteristics. The code is then used for indexing into the database of plans to retrieve a process plan.

The Generative approach is more versatile. It tries to capture the manufacturing logic and reasoning behind the synthesis of process plans. It synthesizes process information to create a process plan for a given part automatically. The difficulty lies in capturing and implementing the logic and methodology of the process planning function.

There have been some attempts to use the expert system technique to automate process planning because of its potential to attack the problems faced in implementing generative systems. Some examples are: TOM[9], GARI[10], SIPP[12], and Hi-Mapp[14].

But more progress is necessary in order that automated process planning systems can be used in practice. Specifically, one needs to tackle the deficiencies of tolerance information and Integrated Tool Database.

Tolerance information is important for process planning in several ways. It is used for checking the technical feasibility of manufacturing components on available machines. It also influences the selection or design of jigs and fixtures. Relative tolerances (viz. concentricity, perpendicularity, parallelism, etc.) are crucial for determining datum surfaces and the proper sequence of machining operations.
Tool selection is another important constituent of the process planning activity. In selecting a proper tool for a given operation, geometric compatibility is perhaps the most important criterion. It is essential to deal with these issues so that a generative process planning system can find significant application to real world problems.

2 Relevance of AI to Process Planning

The primary objective of the planning activity is to select the operations to manufacture the part, and to determine the sequence in which they will be performed logically. In deciding the operations to be performed, the planner has to reconcile the differences among the following:

- constraints placed on the operations by the features of the part,
- the availability and suitability of the machine tools on which they will be performed, and
- the requirements of previous and subsequent operations.

This task of deciding the operations and their sequence is generally found to be quite time-consuming. Normally, the process planner resorts to a trial-and-error method based on his experience before arriving at a reasonable sequence of operations to manufacture the part. The difficulty lies in being able to keep track of all the requirements imposed on the planning process by a number of factors related to the part specification such as shape, dimensions, special features, tolerances, etc. The limited manufacturing facilities available impose additional restrictions. The planner is often faced with a number of alternatives, and could be swamped by the details of deciding on what action to take in a particular situation. An arbitrary choice could aggravate the situation during the later stages of planning. Faced with numerous possibilities to choose from, the planner depends heavily on prior experience to develop a solution within a given time frame.

The activities at this stage could be viewed from the perspective of the planning problem in AI[13]. Planning can be considered to be a problem-solving task in which there is an initial state of the problem of interest, a desired goal state, and a set of operators which can transform one state into another. The task is to determine a sequence of actions or operations to effectively reach the goal state from the initial state, while respecting the problem related constraints. Analogously, in process planning, we need to find a sequence of machining operations, which, when performed on the blank (or raw material), give the finished part.

One of the major concerns in planning is the problem of interacting subproblems. This arises whenever a problem has a conjunctive goal, that is, when more than one condition has to be satisfied. The order in which the sub-goals are to be achieved is often not specified in the problem, but can be critical to finding a solution.

The linear assumption heuristic (which states that sub-goals are independent and thus can be sequentially achieved in any order) was used in early planning algorithms and helped to reduce search, but led to a lot of backtracking. It first used an arbitrary ordering, and later, when unacceptable interactions were detected, it had to backtrack.

Alternatively, it is better not to order operators than to order them arbitrarily. This strategy establishes a partial order of problem solving operators by considering their preconditions, and later imposes some particular order only if this is necessary for eliminating problems which might arise from picking an arbitrary ordering. An important aspect of this approach is that it is constructive; planning decisions are made only when the planner is sure that they will not interfere with past or future decisions. The planner starts with a task (which could have a conjunctive goal) which has to be reduced to primitive tasks. The
aim is to synthesize a task network whose terminal nodes are all primitives. It begins with a sketchy task network and proceeds to augment it by making choices about what to do and in what order to do it.

With this backdrop in mind, planning could be decomposed into two problems: Plan Generation and Plan Coordination. The former is a domain-specific deductive problem, while the latter is more general in nature and relatively independent of the domain of application.

In the development of any plan, there is some flexibility in the way operators are ordered in time. Some operators have to be strictly ordered according to a known sequence; for others, it is not so critical what operator precedes or follows it. The concept of concurrent or interleaved actions allows us to model this, and the planning process can take into account the flexibility provided by these two situations. Constraints allow the planner to keep track of interactions between sub-problems so that steps can be taken to resolve contradictions when they are detected.

3 Issues and Methods

3.1 Representation

The format in which the part geometry is stored is important. CSG and b-rep schemes, which are used by most solid modelers, are not quite suited to the needs of the process planning task.

A feature-based representation scheme is more appropriate because it captures the semantics of the part design and reduces the burden of functional feature recognition. The idea in this representational method is to interpret each feature as a working element in the machining process. Since the vast majority of process planning knowledge is symbolic, it stands to reason that the chosen data structure should promote symbolic manipulation of conceptual information. The task of compiling a knowledge base (in terms of manufacturing rules) is simplified, since human experts are more familiar with form features. Recommendations about choice of the proper machining process could be facilitated by the use of features. Also, this scheme makes it easier to perform the overall analysis (geometric reasoning) of the part - a task which is crucial for gaining a proper perspective of the entire planning task at the outset.

The scheme should be expressive enough to represent attributes which may be geometric, topological, or technological. Data structures used for part representation consist of three kinds of statements. They have some predefined attributes for describing each element. It is not necessary to assign values to every attribute while specifying part geometry: only those which can be directly read off the part drawing need be assigned.

For the case of axisymmetric rotational parts, the statements and their attributes could be:

1. Feature: Also referred to as Main Element. This is for the overall or gross shape of the part and includes the following types: Cylinder, Hole, Cone, Int-taper, and Center-drill. The attributes for specifying these element types are: name, type, length, left-position, right-position, diameter, left-diameter, right-diameter, angle, left-neighbor, right-neighbor, surface-finish, hardness, finishing-elements and relative-tolerance-specs.

2. Finish-element: These specify the finer details of the part - the chamfers, fillets, rounds, grooves, threads, knurls, etc. The attributes pertaining to these are: name, type, feature-on, feature-end, dim1, dim2 ... The attributes dim1, dim2, etc. have different interpretations for different types of finish-elements.
Cyl dia 2.5 leng 2.0 l-pos 0.0 name C1
Cham on C1 end left dim1 0.1875 dim2 45
Thr on C1 end left dim1 1.8125 dim2 0.125
Gro on C1 end rt dim1 0.1875 dim2 0.187
Con l-nbr C1 r-nbr C2 l-dia 3.5 r-dia 4.5
Cyl dia 4.5 leng 1.5 r-pos 5.0 name C2
Hol dia 1.25 l-pos 0.0 r-nbr H2 name H1
Cham on H1 end left dim1 0.0625 dim2 45
Hol dia 2.0 r-pos 5.0 leng 2.25 name H2
Fil on H2 end left dim1 0.25
Rtol type conc ref H2 elem C2 size 0.001

Figure 1: Sample Part and Description

3. Relative-Tol: These are for expressing the relative tolerances between features. The types are: concentricity, perpendicularity, parallelism, etc. The attributes in this case are: name, type, base-reference-feature, tolerated-feature, and amount-of-tolerance.

These three types of statements are sufficient for the complete specification of a rotational part. A sample description is shown in Figure 1.

3.1.1 The Tool Database

Tool selection is one of the important functions to be performed in process planning because the tool influences the surface quality and operation cost. For every scheduled machining operation, an appropriate cutting tool must be chosen.

This subject has not yet developed deeply enough to have a systematic algorithmic way for detailed and optimized selection of all the features of a tool. Heuristic production rules are, therefore, a good way to approach this problem.

Tool selection must take into account the problem of geometric compatibility of tool and workpiece besides deciding about other attributes of the tool. In order that a tool geometry be specified in a process plan, a representation scheme for tool geometry is necessary. Certain descriptors can be identified for completely specifying the geometry and orientation of tools. Of these, some pertain to the tool geometry itself, while others depend on how the tool has been mounted on the turret.

The descriptors for lathe tools are: Nose Radius (RN), Virtual Tool Position (XN, ZN), Nose Angle (AN), Nose Width / Drill Diameter (WN/DD), Cutting Edge Angle (AC), Setting Angle (AS), and Setting Position (XS, ZS). Figure 2 shows the various elements of tool geometry.
A library of tools available to the process planner can be maintained. This library is loaded into memory at the stage when the machining processes have been identified and tool selection is to commence.

**Tasks and Sub-tasks**

A plan can be developed as a task network. Tasks are of two kinds - Primitive and Non-primitive. For the domain of axisymmetric rotational parts, the primitive tasks are: Facing, Roughing, Finishing, Rough Boring, Finish Boring, Center Drilling, Drilling, Grooving/Necking, Thread Cutting, and Tapping.

For each specified primitive task, we must be able to predict its effects on the blank or the partly machined workpiece. For this, a complete description of the operation is necessary. We need to know:

1. The limits of the machining operation
2. The tool to be used
3. The machining parameters

The non-primitive tasks influence the different characteristics of the primitive tasks or operations. They select processes, tools, and machining parameters. Besides these high level tasks specific to process planning, there are others which maintain the task network, set up partial sequences, handle those parts of the algorithm which deal with truth maintenance and violation detection, and project the effects of operations.

In the data structures used, appropriate attributes are needed for denoting the temporal and hierarchical relationships between tasks.

### 3.2 Global Analysis

It is necessary to analyze the data to obtain the overall characteristics of the part. This information (e.g. gross dimensions like maximum diameter and total length, best surface finish required, accuracy, etc.) is important for checking the feasibility of manufacturing the part on a given machine tool. The analysis also helps in making decisions about part holding. On the basis of this information, it is possible to categorize the part as single-phase or multi-phase. For example,
the positions of the cylinder of biggest diameter (BDC) and holes of biggest and
smallest diameter (BDH and SDH) are important in deciding whether a rotational
part can be machined in one phase or whether it is necessary to “end-for-end” it.

3.3 Task Reduction

The principal tasks in process planning are process selection, sequencing, tool
selection and machining parameter determination. Of these, process selection
needs to be done first because the remaining tasks all depend on it.

Each clause describing a geometric element of the part is a specification of the
state which has to be finally achieved. Domain-dependent plan generation rules
are needed to reduce these goal specifying statements to simpler sub-tasks. At
the first level of hierarchy, the aim is to achieve the goal state - as specified by the
working memory elements pertaining to part description. This can be treated as
a Conjunctive Goal since the part description consists of a number of descriptor
elements, all of which must be satisfied at the end. Rules for task reduction draw
upon the data from the part database. They go through the descriptor elements
and select appropriate processes for each. Some partial sequencing information
is also generated.

Processes

Each descriptor element denotes a feature on the part, and it is necessary to
determine the process or processes required to “achieve” that element.

The choice of the necessary operations or processes depends on several factors.
It depends not only on the particular element being considered, but also on the
current state of the part. For example, if the current state of the blank is a solid
cylinder, to obtain a hole of diameter 1.5 inches, the processes required would
be center-drilling, drilling and boring, whereas if the blank already had a hole
of diameter 0.5 inch, boring alone would be sufficient. The selection of processes
is thus a function of the shape of the feature to be machined, the surface finish
required, and the state of the workpiece.

This part of the process planning activity can be considered as the highly
domain specific “Plan Generation” stage. The heuristic information pertaining
to process selection could be coded in the form of production rules and stored in
the production memory of the production system model.

Rules for task reduction perform a twofold function. They elaborate what
processes are to be used for which features and specify the necessary partial
sequences among the processes for that particular feature. For example, reaming
would be scheduled after drilling for any hole that requires drilling and reaming.

Proceeding in this manner, appropriate processes for all the features are se-
lected, and some partial sequencing information is also generated. Since the way
in which the reduction has taken place is sensitive to the characteristics of the
blank immediately preceding the operation, it is important to record this fact so
that any harmful interactions can be avoided. To this end, the concept of reduc-
tion assumption intervals[18] is used to record the pertinent facts on the basis
of which the operations were selected. This information would be useful later if
some other operation could potentially interfere with this state, thus forcing a
sequence between this and the interfering operation.

It is important that the effects of performing the operation on the workpiece
be predicted. This is necessary for two reasons:

1. The task reduction for other features not yet reduced could depend on it.

2. The effects should be checked against existing assumption intervals for po-
tential contradictions.
The selection of cutting tools is part of the detailed planning of the part and is performed after processes have been selected. It is necessary to determine the correct size and shape of the tool, and therefore, requires information about the feature to be machined and the machining process to be used to create that feature.

For a given operation, the selection is dependent principally on the type of operation and the geometry of the element being machined in that operation. For example, only drilling tools can be used for drilling processes and a tool of the shape shown in Figure 3 cannot be used for facing a shoulder. The fillet radii at the shoulders or steps are very important for deciding which tool to use since this places a restriction on the tool nose radius.

In an earlier section we discussed a scheme for representing tools which provides us the facility to describe the geometry of all kinds of tools used on a lathe for machining rotational parts. This scheme is the foundation for the tool selection method. The major task in tool selection is basically a matching of element requirements and tool geometry. Based on its geometry, it is possible to determine the various types of operations for which a tool can be used. The knowledge regarding how to decide for what processes the tool can be used and how to match a tool to the geometric requirements of the element being machined could be coded in the form of production rules.

Two tasks need to be performed – determining what type or family of cutting tools can successfully manufacture the part, and determining a proper tool size to satisfy the constraints of the feature.

3.4 Sequencing

Among all the tasks in process planning, sequencing is the most involved. It produces what is known as the “routing” for the given part. It is here that all the factors of part shape, relative tolerances, and grouping operations are brought to bear in order to create a routing that satisfies all the constraints.

The task reduction phase, in which the process selection is done, provides us with partial sequences among some of the operations. But, finally, a total order among the operations is required so that a definitive routing may be produced.

The concept of “assumption intervals” is useful here. The task network is progressively developed by selecting processes and predicting their effects. At the same time, potential interactions with previously established intervals are detected. For each such interaction, there are three alternatives -

- to put the violating task after the potentially violated task
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- or before it.

- in case neither of these alternatives is feasible, (possibly due to some other constraints), we need to re-do the reduction (if it is a reduction assumption interval being violated) or the projection (in case of a projection assumption interval).

Thus some extra order is imposed on the operations by these considerations.

In case a complete order is not reached on the basis of the above violation detection and avoidance mechanism, some other criteria may be necessary to augment the sequencing.

Grouping of operations can be done on the basis of similarity of type. For example, all roughing operations can be grouped together, as can all finishing operations. But grouping is secondary to the requirements imposed by the relative tolerances. Similar tools can be another basis for grouping of operations. In fact, as far as possible, different elements of the part are machined using the same tool, and this imposes some additional order on the operations.

If two elements of the part geometry have a relative tolerance specification, the relative tolerances are taken care of by creating one of the following constraints:

1. They should be machined in the same holding position, i.e. in the same phase.
2. One of them should be finish-machined first, and then, using that as the holding surface, the other should be machined.
3. A separate finely finished surface must be created, to be used as the holding surface. Both the elements should then be machined using that holding surface (albeit in different phases).

These constraints are manifested as protection intervals and are thus incorporated into the task network reduction mechanism. This ensures a proper ordering of the machining operations.

4 Concluding Remarks

In this paper, an approach for developing an automated process planning system of the generative type is described. The potential for producing efficient machining plans for 2-D axisymmetric rotational parts is examined. It is anticipated that the technique can be extended to cover the cases involving 3-D prismatic parts.

A feature-based representation scheme is used for describing the part. The objective is to synthesize a machining plan which provides a complete operation sequence for a given part. Criteria used for proper sequencing include constraints due to relative tolerances, coalescing of similar neighboring operations, and grouping of operations by similar tools.

Planning concepts in AI offer a very good tool for handling the kind of problems faced in process planning. The concept of assumption-interval violations is particularly useful for representing constraints on the sequencing of operations and detecting possible harmful interactions, thus helping to create better order among them. The concept also enables us to take into consideration relative tolerances and the consequent constraints. A production system model provides the basic framework in which to solve the problem.

References

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