# Observing Machinists' Planning Methods: Using Goal Interactions to Guide Search

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*The following paper describes a model of expert planning behavior, and suggests strategies observed in machinists' behavior that might improve planning performance when applied to other domains. The domain is the design of manufacturing plans for machined parts. The expert machinist uses a planning method which novices do not use. The expert searches for interactions between the problem's goals, then uses the results of the search to guide the construction of a plan that avoids the interactions. Additionally, the expert knows how to divide the problem into two relatively independent subproblems. The subproblems are solved separately and the results merged. A portion of the model is implemented in a program called* ***Machinist****, which has successfully created machining plans that were better then those of a machinist with 5 years experience.*

## INTRODUCTION

This paper briefly discusses the planning methods observed in expert machinists, and compares behavior of apprentice machinists to that of a program, ***Machinist*** that implements these planning methods. Also discussed are a number of the methods observed in the machinist's planning behavior that could be applied to other planning domains to improve performance.

***Machining*** is the art of producing metal parts using a variety of power tools to shape metal. It is a highly skilled task requiring 10 to 15 years to become accomplished. Expert machinists are an important resource for almost all manufacturing industries, but there are relatively few highly experienced ones.

The data were gathered from a series of twenty six verbal protocols over a year and a half. Two subjects with more than 15 years experience were studied. Protocols of the machinists behavior with a more detailed analysis are discussed in (Hayes, 1987a). The implementation of the program, a more extensive discussion of it's performance, and a synopsis of work that this research is based on are included in (Hayes, 1987b).

## INTERACTIONS MAKE THE PROBLEM DIFFICULT

A major problem that machinists confront in planning is "interactions" between the different "features" that are cut into the part. ***Features*** are the individual geometric shapes that are cut into a block of metal. ***Feature interactions*** happen when cutting one collection of features affects the way in which others can be made. The difficulty in making a plan is to find an order in which none of the features interferes too seriously with producing the others.

Most commonly, feature interactions are caused by clamping problems; producing one feature destroys the clamping surfaces needed to grip the piece while cutting another feature. A feature interaction is shown in figure 1. The piece has two features on it: an angle and a slot. If the angle is made first it is difficult to clamp the piece so that the slot can be cut. The right hand vice jaw must press on the angled surface. This is an unstable situation because the part may be forced upward out of the vise. The angle can be said to ***interact with*** the slot. A simple reordering or the features can avoid this interaction.

## THE MACHINIST'S PLANNING METHODS

Examples for this paper were taken from one protocol from a machinist planning how to make the part shown in figure 2.

The protocol showed that the human plans by first scanning the problem specification, (an engineering drawing and notes), and noting cues that indicate problems and feature interactions. Associated with each of these cues, the machinist has a set of restrictions that will help avoid that problem or interaction.

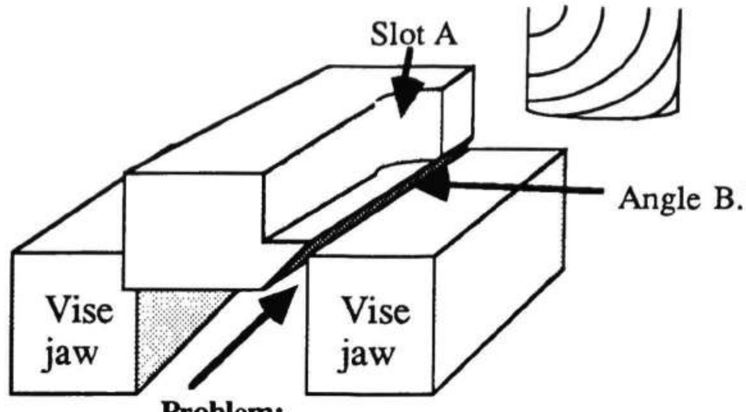



**Figure 1:** ***Feature Interaction***: The slot must be cut before the angle.

The features that drew the machinist's attention during the protocol were the large features: C, A, and D, and the large angles: E1, E2, B1 and B2. These features are of particular interest, because they cause the part to have an irregular shape and hence make clamping difficult. When clamping is difficult, the part can be clamped only in restricted ways to produce other features.

Next, the machinist investigated these attention attracting features in more detail. He explored the ways in which each feature restricted and affected others. During this stage he also grouped features into sets that could be made during the same clamping operation. All features in a group could be made with the same side facing up. Grouping makes it easier for the machinist to plan because entire groups are manipulated as single components; all restrictions on any feature in the group apply to the whole group. The strategy effectively reduces the complexity of the planning process. Even so, the machinist eventually found it difficult for keep track of all the restrictions on all the groups at the same time, so he drew a picture which is represented by the graph in figure 3. This is an ***interaction graph***.

Whole groups are represented by a single letter in the graph. For instance "C" represents the group consisting of C, R, and the four holes; and "E" represents the group E1, E2, G1, and G2.

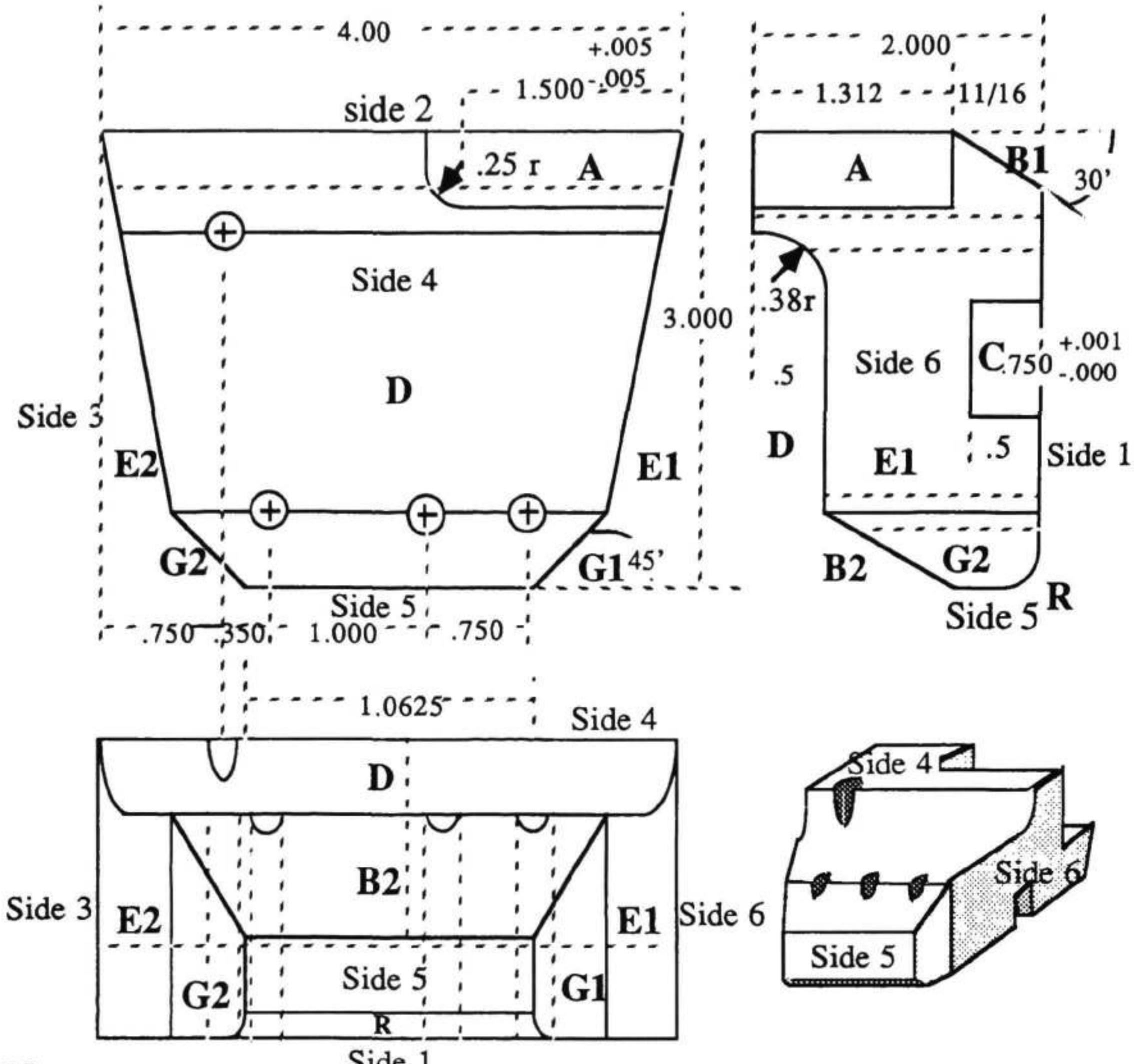
The order restrictions represented by this interaction graph are: either shoulder A or group C can go first in either order. Then the angles in group B (B1, B2) can be cut, followed by the E group, followed by D. The numbers beside the letters indicate which side must face up while that feature group is cut. (All the sides in figure 1 are given numbers from 1 - 6). B and E have no numbers because they are angles; the piece must be tilted when they are cut, so no side faces directly up.

Before any of these features can be cut several preliminary steps must be taken. Typically, three orthogonal sides (a group of sides that touch on one corner) must be machined smooth and square to each other before a feature can be cut. This is so that there will be precisely defined sides from which to measure feature positions. If the sides are not accurate, the feature position will not be accurate.

This process of smoothing the sides is known as ***squaring***. There are strict rules for squaring that must be followed so that the minimum amount of material is wasted, and accuracy maintained. The squaring rules are dependent only on the characteristics of the starting material. They are independent of the the features to be cut so squaring rules are relatively invariant for all parts regardless of their final shape, while on the other hand, the feature interaction graph always changes from part to part, even when the final shapes are very similar.

The machinist drew a small diagram indicating the order in which he intended to square up the sides. He explicitly drew out only out the first three squaring steps (so he would have three orthogonal sides) and left the others to be decided later. Figure 4 shows the order that he decided on. Steps in the horizontal row (eg. 4, 5, 6) can be done in any order. The numbers indicate which side faces up.

Next, the squaring graph must be merged as efficiently as possible with the interaction graph. The more steps that can be overlapped the better because the final plan will be shorter. Typically. if the same side faces up in two steps, they can be merged, providing that none of the




**Notes**

| | |
|---|---|
| BOM 2.5 x 3.1 x 4.25 AL PLT | ALL TOLERANCES ± .002 |
| ⊥ +.001 -.001 | |
| ∠ ± 30'' | |

**Figure 2:** A design for part XI

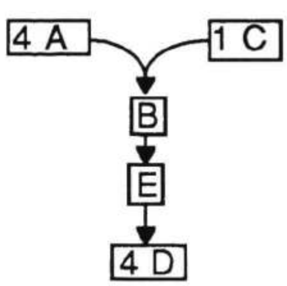



**Figure 3:** The ***Feature Interactions*** for PART XI

"before" and "after" constraints of either graph are violated. Figure 5 shows the two graphs merged.

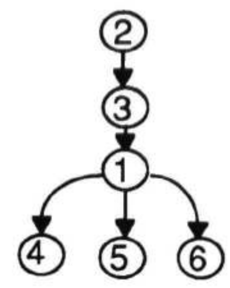



**Figure 4:** The *Squaring Graph* for Part XI

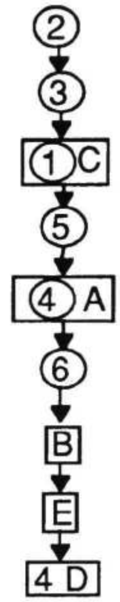



**Figure 5:** The combination of the *Interaction Graph* and the *Squaring Graph*

Lastly the plan is verified. The machinist looks over the plan and checks that there no interactions were overlooked, and that the part can be clamped properly at each step. If the plan does not pass this test he may have to go back to previous planning stages and replan.

The **Machinist** program, discussed in (Hayes, 1987b) implements these steps, except for the verification step and grouping. Forty nine of it's productions identify feature interactions and other problems. Grouping speeds up the planning process but does not generally affect the quality of the plan. Verification is needed only if interaction is missed, so as long as the program stays within the domain of parts containing interactions that it knows about, verification will be unnecessary.

## EVALUATION OF THE PROGRAM AGAINST HUMAN PERFORMANCE

The program's performance was compared with that of four machinists at various experience levels: two second year apprentices, one third year apprentice, and one journeyman with 5 years experience. Each of these subjects was asked to create a machining plan for the same series of three parts. The specifications for the three parts used in the study as well as a few example plans generated by the apprentices, are described in (Hayes, 1987a).

Their resulting plans were judged by two very experienced machinists, each having more than 15 years experience. The program's average performance was better than that of the apprentices or the journeyman. The average scores earned by each machinist or program are shown in figure 6. In fact, Machinist 1 declared the program's plan for Part III to be "Almost the perfect plan. Who ever did this is a man after my own heart." As it turned out, in making the plan for Part III, the program used a heuristic taken from machinist 1. Consequently, the plan coincided with his idea of what was correct and was indeed "after (his) own heart." However, it wasn't made by a man, but a machine.

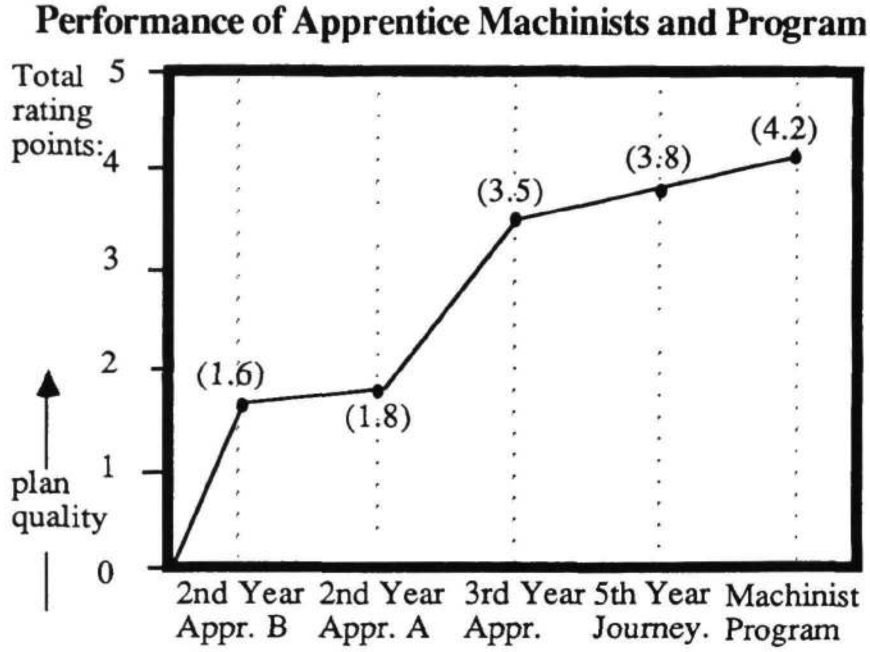



**Figure 6:** Average scores received by each subject

Judging was done in the following way: for each of the three parts there were five plans: one from each of the four young machinists, and one from the program. All information indicating who (or what) created the plan was removed. Independently, the two experienced machinists ordered each set of five plans from best to worst. The best plans were given a score of 5 and the worst 1.

There was fairly high agreement between the two machinists, despite a few anomalies. The Spearman rank correlation of their judgements is 0.92. Thus, the judgements are quite reliable.

One interesting outcome of this test was that it highlighted the difference between the expert machinists and the novices. The novices with less then two years experience showed no ability to spot feature interactions either before or after planning. Not only could they not foresee the problems, they seemed unable to detect that there was a mistake in the finished plan. It seemed that they lacked the perceptual skill that the expert had for identifying feature interactions. This ability seems to be *key* to the expert machinists' time efficiency and accuracy in planning.

Additionally, the novices with less than five years experience were unable to make efficient plans. It was difficult enough for them to make working plans at all. They used rote methods for many steps. It was not till about 5 years that any of them started to use more flexible methods that allowed more efficiency in the plans.

## CONCLUSION

The planning steps for expert machinist are:

1. **Orientation:** Identifies the key features interactions and makes an estimate of the problem difficulty.
2. **Exploration of Feature Interactions:** Groups features and explores the ways in which they interact with others.
3. **Integration of the Feature Interactions with a Squaring Plan:** Merges feature interactions with squaring constraints.
4. **Elaborating and Verifying the Plan:** Checks to see that the plan is correct. If there is an error, he makes a fix or replans.

The **Machinist** program implements this method and produces plans that experts judged to be comparable or better than those of a 5 year journeyman. The plans are very similar in form to those that expert machinists produce. This study also showed that planning methods of experts were very different than those of novices: novices had neither the experts' ability to foresee problems nor their flexibility in planning.

The machinist's method of using patterns to spot problems first and plan around them has potential for improving planning efficiency in other expert domains. Other behaviors seen in machinists behavior that could be applied to other domains are: grouping, to cut down complexity of the plan space; and calculating the varying constraints (features interactions) separately from the invariant constraints (squaring) and latter merging them. This technique simplifies planning by dividing the problem nicely into two relatively independent sub-problems.

## ACKNOWLEDGEMENTS

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