Fixture-Driven Hybrid Process Planning

Alexei Elinson
Dept. of Computer Science
and Institute for System Research
University of Maryland
College Park. MD 20742
elin@cs.umd.edu

Dana Nau
Dept. of Computer Science
and Institute for System Research
University of Maryland
College Park. MD 20742
nau@cs.umd.edu

Abstract

Automated synthesis of manufacturing process plans has been attempted through many methodologies for a wide range of manufacturing problems. In some cases, such as the manufacture of machined parts, these attempts have not been fully successful: to date, it has not been possible to develop purely generative systems to synthesize complete realistic plans for a wide range of realistic machined parts. In this paper we propose a new approach to process planning for machined parts, which integrates case-based reasoning and generative components.

Introduction

An automated process planner providing realistic process plans for a reasonably wide spectrum of products would make a great impact on industrial practice; and mechanical engineering and industrial engineering researchers have done much research on developing process planning systems. However, attempts to build purely generative process planners have had only limited success, primarily because this domain lacks sufficiently well-defined rules and approaches to work across the entire problem domain, and engineers developing process plans have to heavily rely on personal experience and informal manufacturing practices.

In contrast, a number of successful semi-automated systems have been developed using an approach called *variant process planning.* Variant process planning is somewhat similar to case-based planning, in the sense that plans are stored in a database, so that they can be retrieved and modified for use in new planning problems. However, one of the primary differences is that the plan modification is done by the human user rather than by the computer system.

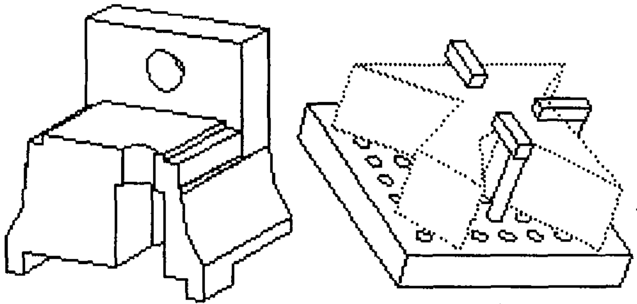
If successful ways could be developed to extend the variant approach by using case-based reasoning techniques to do some of the plan modification automatically, this would significantly increase the practical utility of such systems. As a first step in this direction, we give a brief description of a new approach to process planning which reuse old process plans, adapting them to new designs.

Background

Increasing competition is challenging the manufacturing industry to bring new well-manufactured and competitively priced products to market as quick as possible. Long ago it was recognized that one of the most important steps to this goal is a making of effective *process plans* (Chang 1990). A process plan unambiguously describes how a design can be manufactured from a corresponding stock and consists of ordered sequence of descriptions of manufacturing processes, where all relevant parameters of each process are specified. Process plans are similar to plans considered in AI literature—they are synthesized to achieve some goals and manufacturing processes used in them can create or delete preconditions for other processes.

Despite the achievements of the past 20 years, the development of a good approach for automating process planning remains a very important and very difficult problem—existing systems are able to reliably handle only very restricted classes of designs (often not producing realistic process plans) and/or require very intensive human interaction. There are two primary approaches to CAPP—the variant and generative approaches. Generative process planning is analogous to plan generation in AI domains: the goal for the process planning system is to develop a complete plan for the proposed product design. Variant process planning is in some respects similar to the plan adaptation and reuse techniques explored by AI researchers, except that although the plan retrieval is done automatically, the plan adaptation is done manually.

In process planning practice, variant techniques are the tools of choice: they currently support almost all practical implementations of Computer-Aided Process Planning (CAPP). Several variant systems are commercially available and have provided significant benefits—but despite the popularity of this approach, variant process planning has some well known drawbacks. A great deal of research has been done on generative approaches, and a number of experimental systems have been developed for various aspects of process planning. However, generative process planning has proved quite difficult. Most existing systems



(a) (b)

Figure 1: (a) a real-life prismatic design; (b) a machine-clamped prismatic design.

work only in restricted domains, and have not really achieved significant industrial use.

We are in the early stages of developing a new approach to process planning—a hybrid between the variant and generative approaches that attempts to combine the best characteristics of each, while avoiding the worst drawbacks of each. In this paper, we give a brief survey of some of the requirements and characteristics of process planning and how our approach will address them.

Manufacturing of Prismatic Designs

Products manufactured by modern industry are very diverse and can be divided into domains different from each other with respect to processes and practices used to manufacture products belonging to them. Most of existing CAPP systems is able to handle only some specific domain of products, as expertise in some domain usually is irrelevant to any other domain.

One of the most populated domains of mechanical parts is a domain of *prismatic designs* (Figure 1 (a)) and it was often addressed by the researchers. Its formal definition is unknown though it is a common term, but its meaning is clear—it includes designs whose overall shapes cannot be conveniently manufactured by such operations as lathing and pressing and has to be manufactured using such operations as milling and drilling. In our work we address a domain of prismatic designs manufactured on 3-axis machining centers.

Process plans for such designs have to include descriptions of material-removing operations (e.g., milling) and of material-non-removing operations such as tool changes and fixturing operations. Fixturing operations fixate workpieces making some parts of them available for consecutive material-removing operations. Figure 1 (b) shows a fixturing device—machine-clamps applied to a prismatic workpiece. Parameters of fixturing operations depend not only from geometry of corresponding workpieces and material-removing operations (e.g., geometry and location of parts of workpieces to be removed), but also from non-geometrical parameters of manufacturing operations such as feeding and rotating speeds, types of tools.

Industrial process plans have to be realistic and effective—they have to use manufacturing processes and tools available in a workshop according to manufacturing practices, and have as low costs (caused by amortization of equipment) and require as short time as possible. In modern industry the significant part of material-removing operations can be performed automatically, using numerically controlled tools, but fixturing operations often have to be performed manually. It makes them expensive and time-consuming, and effective process plans have to include as few of them as possible. Any material-removing operation interacts only with a small part of a workpiece and it is relatively easy to synthesize some sequence of them for a design, but to plan fixturing operations it is necessary to consider workpieces as whole.

Prismatic Designs & AI

Though process plans are very similar to plans discussed in AI literature, the domain of planing for prismatic designs has some properties very different from the properties of abstract domains addressed by most AI planning systems, and among them are:

- Prismatic designs are 3 dimensional objects and a convenient way to describe them in forms usually used in AI (e.g., predicates) is unknown. Probably, due to the very intensive and diverse relations between different parts of designs (e.g., a part of a design restricts access to another part, an overall shape of a design does not permit some applications of fixturing devices) any explicit descriptions of designs in any of such forms will be impractical. Usually annotated solid models are used to capture designs and any operations upon them are very expensive.
- Results of application of majority of material-removing operations to designs are relatively complex and solid models of workpieces have to be modified to capture them. A lot of AI techniques based on reasoning about more popular representations of objects (e.g., sets of predicates) cannot be used.
- In some cases queries whether a manufacturing operation can be applied to a workpiece are extremely expensive and it is impractical to perform such checks multiple times during traversal of search spaces. Sometimes such queries can be performed only if a complete description of a workpiece to which an operation has to be applied is known and so it is necessary to know all operations which will be performed before the operation to be checked. It makes a usage the least commitment techniques difficult.
- Parts of designs interfere very intensively and a significant part of manufacturing operations performed upon workpieces causes non-local changes of their properties. As a result it is difficult to figure how traditional AI planning techniques, such as "divide

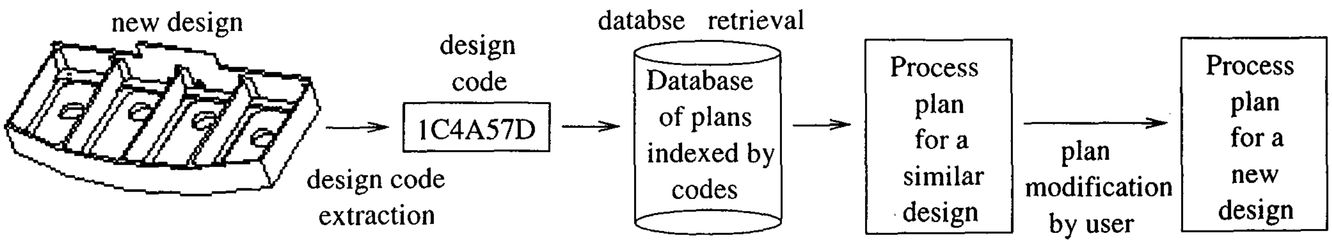


Figure 2: A scheme of control flow in variant process planning.

and conqueror" and hierarchical planning, can be used to plan for whole designs and not only for their trivial, relatively independent parts.

- Usually for any part of a design there exist several (sometimes infinitely many) ways to manufacture it.
- Process plans have to be effective as a whole and often a non most effective manufacturing of some part of a design permits to decrease number of fixturing operations or used tools.
- Well-known rules describing preconditions which have to be satisfied to make material-removing operations applicable are very rough and often do not correspond to manufacturing practices.

Approaches to Process Planning

Variant Approach

Variant process planning (Figure 2) is based on the use of coding schemes. Given a new design D for which a process plan is needed, the process engineer first determines a code for D, and then uses this code as an index into a database to retrieve a process plan for an old design D' similar to D. Then the process engineer modifies the retrieved plan manually to produce a plan for the design D. Virtually all industrial variant CAPP systems use Group Technology (GT) coding schemes.

The basic idea of GT is to capture critical design and manufacturing attributes of a part in a short (8-40 symbols) alphanumeric string, or GT code, that is assigned to that part. The typical GT code consists of two types of positions. In one case, a position describes some global property of the design such as material, size, type, functionality, etc., and its meaning is completely independent of what values are stored elsewhere. In the other case, a position represents some details that are relevant only for certain types of designs, and thus its meaning depends on the values of other positions. Since the 1980's several researchers (Srikantappa and Crawford 1994) have worked on automated code extraction for classes of machined parts. Innate drawbacks of this approach are:

- If the part mix and the set of available processes vary over time, then it may be difficult to find existing designs whose process plans can be easily adapted for the manufacturing of some new designs.
- Codes which describe designs as whole and represent them as short strings are very rough and retrieved process plans are often irrelevant to new designs.
- Probably it is impossible to robustly adapt retrieved old process plans without human interference.

In some respects variant process planning is close to case-base reasoning approach, though techniques used to retrieve relevant old process plans are significantly simpler than techniques used in modern CBR systems. To some extent the usage of such simple methods is due to the fact that variant process planning was introduced more than 70 years ago and became really popular more than 30 years ago when searches of relevant process plans have to be performed manually, but the other reason is that more sophisticated methods permitting to assess similarity/analogy between designs from the manufacturing point of view are unknown[1].

Generative Approach

Generative process planning systems directly synthesize process plan for new designs. For machined parts, the typical approach is to do the the planning on a feature-by-feature basis (features are parts from designs, meaningful from the engineering point of view—i.e., slots, pockets) by retrieving candidate processes from the knowledge repository, selecting the feasible processes on the basis of geometric and manufacturing-related constraints, and combining the chosen processes in a proper sequence. Different techniques were used (e.g., hierarchical planning, rule-based expert systems), a number of experimental systems have been developed for various aspects of process planning (Mäntylä, Opas, and Puhakka 1989), but most existing systems work only in restricted domains, do not synthesize complete process plans (usually fixturing operations are omitted) and with single exception (Geelink et al. 1995), have not really achieved significant industrial use.

We think that primary reasons which makes a development of a robust generative process planner so difficult are that the manufacturing practices are too complex to be captured only in a form of rules or facts,

[1] The description of existing methods as well as the description of our approach to this problem can be found in (Elinson, Nau and Regli 1997).

and that to generate a sufficiently effective process plan containing fixturing operations its is necessary to consider designs as whole and not only as collections of independent features.

Hybrid Approach

By a hybrid approach, we mean any approach that attempts to exploit knowledge in existing plans while generating a process plan for a new design. Though some approaches have been proposed (two are described below), researchers have not yet developed comprehensive solutions:

- Park et al. (Park et al. 1993) describe an approach for acquiring knowledge useful for generating process plans. Given a process plan for a design, it uses inference rules to find the explanations behind the plan (what part of the plan did what). Then it stores the knowledge as a schema, which describes how in general to make some collection of features. Planning is done by seeking relevant schemas and inserting the necessary values to construct a valid plan. A relevant schema is one with the same collection of features. This is a very simple design similarity measure: it uses no other manufacturing information (such as precedences or tolerances) to identify the relevant schema, does not consider feature interactions and generates plans which include only material-removing operations.
- Marefat and Britanik (Marefat and Britanik 1994) propose a hybrid approach that captures plan knowledge that specifies the processes necessary to make a certain feature (with a specific size, hardness, surface finish, and tolerances). Planning decomposes a design by generating sub-plans for each feature and then searching the old sub-plans for the most appropriate one. The most appropriate old plan is the one that makes a feature that is most similar to the new design's feature. Similarity here is hierarchical: the feature must be the same type, then the same dimensions, then the same tolerances. Corresponding to each level of feature properties are process capabilities. Because the new and old features will be different at some level, the old plan is modified: the planner keeps the process information that corresponds to the levels at which the old and new features are identical, discards the remainder, and generates new information using process capability rules. This approach uses features which do not correspond to manufacturing operations and makes an unrealistic assumption that each feature can be made independently from other features and a corresponding workpiece.

As these examples show, the existing hybrid approaches have limited capabilities. A robust hybrid approach must consider feature interactions, precedences, tolerances, and other critical design information that impact process planning, and address such problems as storage, classification and retrieval of useful design and process planning information.

Our Approach

We think that a hybrid variant/generative CAPP system, working in the domain of prismatic designs manufactured on 3-axis milling centers[2] will be able to keep the best features of the approaches described above, while avoiding their worst drawbacks, if it will have the following characteristics:

- In order to decompose the planning process for material-removing operations and still produce realistic plans, it considers designs not as collections of features but as collection of slices--the smallest parts of designs which as far as only material-removing operations are considered can be manufactured more or less independently from each other (Elinson et al. 1997).
- In order to effectively synthesize realistic sequences of material-removing operations for slices, it synthesize sequences for the majority of slices in a generative way using a relatively simple collection of domain-dependent rules, and adapts fragments of old process plans for remaining more complex slices.

  A collections of rules used by a system does not have to be complete—to permit to generate a fragment of process plan for any slice, but it has to be sound—it has to generate only realistic fragments of process plans.
- To be able to synthesize an effective process plan, a system considers designs as whole and tentatively decides in which order different parts of designs will be manufactures and which sequence of manufacturing operations[3] will be used.
- A system does not try to select an order of manufacturing of design parts and a sequence of manufacturing operations in a generative way—the methods permitting to do it are unknown—but reuses old process plans of similar designs.
- It does not try to adapt sequences of exact fixturing operations from old process plans to new designs, but uses them as heuristics (Nebel and Koehler 1993) which suggest in what order to manufacture overall shapes of designs, to change orientations of workpieces with respect to machining centers and as a result finds some kind of hierarchical decompositions of given process planning problems.

[2]We think that this approach can be also used in other manufacturing domains.

[3]In this stage the system has to find only an order of orientations which a workpiece will take in the process of manufacturing—not particular parameters of manufacturing operations, and to decide whether some critical parts of workpieces will be processed during some particular workpiece orientations or not.

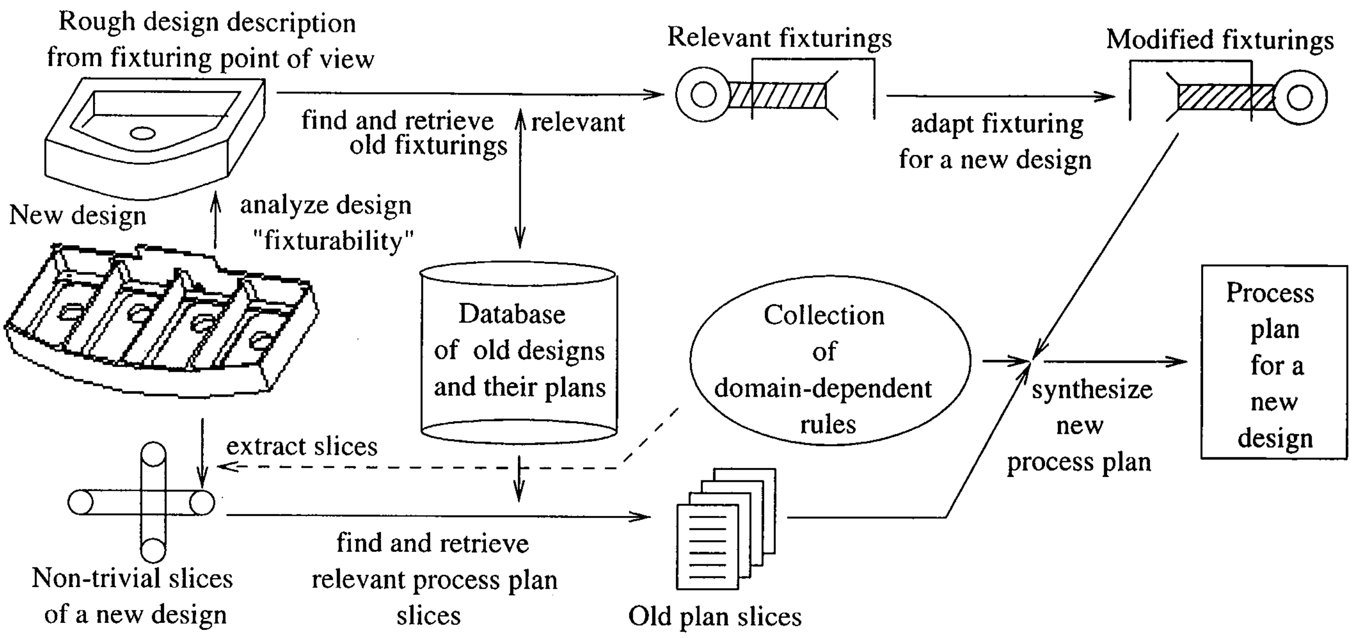


Figure 3: A scheme of the control flow in a fixture-driven hybrid CAPP system (without backtracking).

- To find old designs similar to the new one it uses a machining feature-based design similarity measure able to handle not only geometry of prismatic designs but also their manufacturing properties (Elinson, Nau and Regli 1997).

The work of the proposed CAPP system will consist of two major phases:

- **Preprocessing:** given a database of existing designs and process plans, build indexing and classification structures for search and retrieval;
- **Planning for new design**: given a new design, use the classification structure to retrieve relevant planning information from the database, and use this information to synthesize a plan for the new design. Particularly, the following stages will be performed:
  - Find an old design and a corresponding process plan, such that the old and the new designs are close to each other and that *fixturings*—sequence of fixturing operations—used in the old process plan are probably similar to fixturings which can be used to manufacture a new design;
  - Using old process plan synthesize an abstract process plan for the new design, which describes in which order the overall shape of the design will be manufactured[4];
  - Adapt the fixturings of the old design to the new design;
  - Generate a process plan for the new design based on the abstract plan and the modified fixturings, using domain specific knowledge captured in the form of rules and adopting fragments of old process plans if necessary.

The simplified[5] control flow of a CAPP system based on the proposed approach is shown in Figure 3. In the upper branch the CAPP system takes a new design, analyzes it and finds a *design signature*—design description which captures only design properties relevant to the selection of a sequence of fixturing operations and the selection of an order in which parts of the design can be manufactured sufficiently effectively. Then the system performs search in the database of old designs and process plans and retrieves relevant old designs and their process plans—designs with compatible design signatures. The system extracts fixturings and an order of design parts from the description of some old design and its process plan, and adapts them for the new design.

In the lower branch the CAPP system takes the new design, analyzes it with respect to the collection of domain-dependent rules, which stores the only description of the domain available to the system, and extracts all non-trivial *slices*—parts of the design which according to a domain-dependent knowledge captured by the rules cannot be manufactured at all or sufficiently effectively, makes a search in the database and retrieves fragments of process plans describing manufacturing of

[4] Note, that sequence of fixturing operations which was used during a manufacturing of a design to some extent defines an order in which parts of a design were manufactured and vise versa.

[5] Among other omissions the scheme does not show any backtracking and ignores exchange of information between two branches of the control flow.

slices similar to the non-trivial slices of the new design. For some non-trivial design parts similar parts of old designs will not be found in the database, and their process plan fragments will either be synthesized with the help of a user or will be generated using the rule collection.

Then the system generates the process plan fragments for the trivial slices using the collection of rules, takes the modified fixturings, the modified order of manufacturing of design parts, the plan fragments for all design slices and synthesizes a complete process plan for the new design, using the collection of domain-dependent rules. The adapted fixturing operations are completely instantiated during the final synthesis of a process plan and it can be necessary to validate them using the collection of old designs and their process plans.

Conclusions

We think that this approach is practical and promising, but our work is still in the early stages. A number of problems—both theoretical and practical—will need to be addressed before it will be possible to build a robust CAPP system based on our approach or any other approach.

References

Chang, Tien-Chien. 1990. *Expert Process Planning for Manufacturing.* Addison-Wesley Publishing Co.

Elinson, A., Nau, D.S., and Regli, W.C. 1997. Feature-based similarity assessment of solod models. In Proceedings of ACM Solid Modeling Conference.

Elinson, A., Herrmann, J.W., Minis, I.E., Nau, D.S., and Singh, G. 1997. Toward Hybrid Variant/Generative Process Planning. In Proceedings of 1997 ASME Design Engineering Technical Conferences.

Geelink, R., Salomons, O. W., van Slooten, F., and van Houten, F.J.A.M.. 1995. Unified Feature Definition for Feature-Based Design and Feature-Based Modeling. In Proceedings of ASME Computers in Engineering Conference, 517-534. ASME.

Mäntylä, M., Opas, J., and Puhakka, J.. 1989. Generative Process Planning of Prismatic Parts by Feature Relaxation. In Proceedings of 15th ASME Design Automation Conference, 49-60, ASME.

Marefat, M., and Britanik J. 1994. Case-base process planning with hierarchical plan merging. *IEEE*, 165-170.

Nebel, B., and Koehler, J. 1993. Plan Modification versus Plan Generation: A Complexity-Theoretic Perspective. In Proceedings of the 13th Intelligence, 1436-1441, Morgan Kaufmann.

Park, S.C., Gervasio, M.T., Shaw, M.J., and DeJong, G.F. 1993. Explanation-based learning for intelligent process planning. *IEEE Transactions on Systems, Manm and Cybernetics* 23(6): 1597-1616.

Srikantappa, A., and Crawford, R. 1994. Automatic part coding based on interfeature relationships. In Shah, J., Mäntylä, M., and Nau, D., eds, *Advances on Feature Based Manufacturing,* 215-237. Elsevier Science Publishers/North Holland.

Appendix

1. **Integration name/category**: FIDHYPP - FIxture Driven HYbrid Process Planner.
2. **Performance Task**: Synthesis of manufacturing process plans for mechanical designs.
3. **Integration Objective**: Synthesis of *complete realistic* process plans despite the usage of relatively small sets of simple rules capturing domain-dependent knowledge.
4. **Reasoning Components**: Generative process planning (GPP) components for generation of plan fragments for relatively simple parts of designs, synthesis of complete plans and generation of fixturing operations (if necessary); CBR components for synthesis of abstract process plan, some fixturing operations and plan fragments for "not-trivial" design parts.
5. **Control Architecture**: CBR as master & as slave—components are applied in the following order and any of them can require a backtracking: CBR, GPP, CBR and GPP simultaneously and independently from each other, GPP, CBR, GPP.
6. **CBR Cycle Step(s) Supported**: Retrieval, reuse(adaptation).
7. **Representations**: CBR and GPP components works with design descriptions (annotated solid models and feature sets) and process plans—sequences of annotated solid models, corresponding to manufacturing operations.
8. **Additional Components**: User interface.
9. **Integration Status**: Proposed on the basis of previous work, some components are mathematically and practically evaluated.
10. **Priority future work**: Complete implementation and practical evaluation.