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Hierarchical Task-Network Planning for Process Planning for Manufacture of Microwave Modules*

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Abstract

This paper reports on the development of a planning system for an important industrial planning problem. This planner, which is one of the modules in an integrated design-and-planning system called EDAPS, provides an integrated approach to process planning in both the electronic and mechanical domains, specifically in the manufacture of microwave transmit-receive (T/R) modules.

Our planner is based on a modified version of HTN planning. We provide an overview of its operation, and compare and contrast it to how HTN planning is normally done.

This same modified HTN planning strategy appears to be useful in a variety of application domains. For example, as described in (Smith, Nau, & Throop 1996), the basic approach has been used successfully for declarer play in the game of contract bridge. We discuss why this approach is successful in two such diverse application domains.

Motivation

The authors of (Nau, Gupta, & Regli 1995) argued that although AI planning techniques can potentially be useful in several manufacturing domains, this potential cannot be realized without developing more realistic and more robust ways to address issues important to manufacturing engineers. They further argued that by looking realistically at issues important to manufacturing engineers, AI researchers might be able to discover principles relevant for AI planning in other domains. This paper attempts to address both of these objectives, in a manufacturing planning domain quite different from the machining domain described in (Nau, Gupta, & Regli

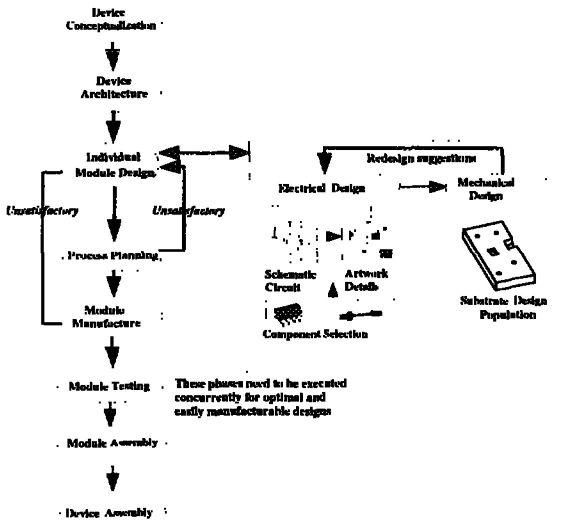

Figure 1: Design and manufacturing cycle for microwave T/R modules.

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*This material is based on work supported in part by ARPA grant DABT 63-95-C-0037, by the National Science Foundation under Grants NSF EEC 94-02384, IRI-9306580, and DDM-9201779, and by in-kind contributions from Spatial Technologies and Bentley Systems. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funders.

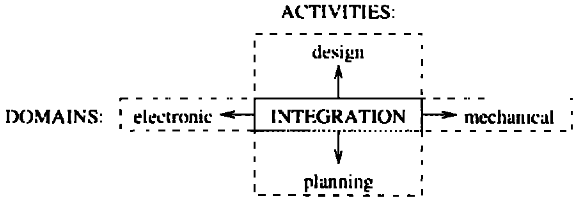


Figure 2: Integration of disciplines for the design and manufacture of complex electromechanical devices.

1995): the design and manufacture of complex electromechanical devices. More specifically, this paper focuses on the use of AI planning techniques for process planning in the design and manufacture of *microwave transmit-receive (T/R) modules.*

Figure 1 illustrates the design and manufacturing cycle for microwave T/R modules, which is highly interdisciplinary in nature. Electronic designers develop the detailed circuitry; mechanical designers design the device to resist shock and vibrational loadings, and develop the assemblies, the heat removal systems, and the housing of the device; and manufacturing engineers apply electronic manufacturing processes (such as lithography, soldering, cleaning, and testing), and mechanical manufacturing processes (such as drilling and milling) to manufacture the end product.

For many manufactured products, the decisions made during the design of the product will determine most of the cost of manufacturing the product. This has given rise to the philosophy of *integrated product and process design* (IPPD), which attempts to take manufacturing considerations into account while the product is being designed. However, in the design of a complex product, this requires coordinating a large interdisciplinary team. In large organizations, this can be a difficult task (O'Grady et al. 1991).

The task of communicating design and manufacturing requirements and design changes across disciplines could be greatly aided by a carefully designed computer system that integrates both electronic and mechanical computer-aided design (CAD) tools, and provides access to process planning and design evaluation capabilities, as shown in Figure 2. Such a system could be used for designing both the electronic and mechanical aspects of a product, analyzing various aspects of the design's performance, planning how to manufacture the proposed design, and evaluating the process plans to provide feedback to the designers about the design's manufacturability.

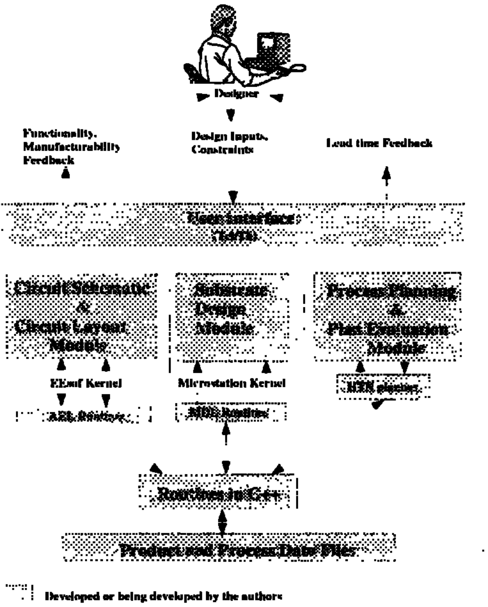
Few existing computer systems can successfully address all of these issues in a single integrated environment—and there are several open questions about the best way to design such a system. To explore these issues, we have created the *Electro-mechanical Design And Planning System (EDAPS)*, a toolkit for microwave T/R module manufacture that integrates electronic and mechanical computer-aided design, electronic and mechanical process planning, and plan-based design evaluation. EDAPS's process planning module generates process plans concurrently with design, and assists the designers in performing plan-based critiquing of microwave T/R module designs.

EDAPS incorporates electronic design, mechanical design, and process planning modules into a single integrated environment. Its process planning module plans both in the mechanical domain, including such processes as drilling and milling, and in the electronic domain, including such processes as via plating, artwork deposition, component placement, and soldering. This allows EDAPS to provide feedback about manufacturability and lead time to the designers, based on process plans for the manufacture of the device.

System Architecture

In the EDAPS system, we want to provide the designers with CAD tools for electronic and mechanical design, and with an integrated process planner for manufacturing processes in both the mechanical domain and the electronic domain. Thus, as illustrated in Figure 3, the EDAPS system consists of three modules that can be invoked from a common user interface:

- In EDAPS's *circuit schematic and circuit layout module*, the designers generate electronic circuitry. An integrated set of packages supplied by EEsof's Series IV (EEsof 1992) software forms the core of this module. On top of these packages, we have developed routines to provide us with application-specific information. We address the circuit layout module in more detail in (Hebbar et al. 1996).
- In EDAPS's *substrate design module*, the designers develop mechanical features of the MIC. Bentley Systems' Microstation CAD software application (Microstation 1995) supplies the set of tools required to achieve this functionality. The ACIS (ACIS 1993) solid modeler is used internally to represent and provide methods to generate and modify features defined in Microstation. We are developing routines in C++ and the Microstation Development Language to integrate Microstation with the rest of the system and to extract and supply relevant manufacturing information. More details are available in (Hebbar et al. 1996).
- EDAPS's *process planning and plan evaluation module*, which is the subject of this paper, creates a process plan for the design, and reports the manufacturability and lead time for the design to the designers. EDAPS employs a *generative* process planning approach; that is, decisions needed to achieve final design specifications are automatically taken by the computer The



EDAPS

Figure 3: System architecture.

process planning module is described in more detail in the next section.

- The coordination of these modules and the exchange of data among them takes place through a user interface written in the *Tcl/Tk* language (Ousterhout 1994). This user interface allows the designers to smoothly interact with the heterogeneous modules that constitute the system.

Process Planning and Plan Evaluation Module

To perform process planning for microwave T/R module designs, we use techniques from *hierarchical task-network (HTN)* planning(Currie & Tate 1985; Sacerdoti 1977; Tate 1977; Wilkins 1984; Wilkins 1988; Yang 1990; Kambhampati & Hendler 1992; Erol, Hendler, & Nau 1994). We have also used this approach in some of our other work (Smith, Nau, & Throop 1992; Smith & Nau 1993; Smith, Nau, & Throop 1996). In EDAPS, process planning proceeds by taking a complex *task* to be performed and considering various *methods* for accomplishing the task. Each method provides a way to decompose the task into a set of smaller tasks. By applying other methods to decompose these tasks into even smaller tasks, the planner eventually produces a set of primitive operations that it knows how to perform directly.

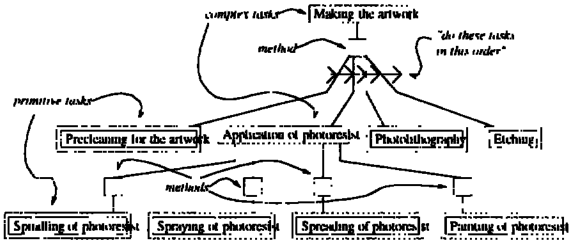


Figure 4: Part of the task network for microwave T/R module manufacture.

As an example, one method for making the artwork for the Microwave Integrated Circuit (MIC) is to do the following series of tasks: precleaning for the artwork, followed by application of photoresist, followed by photolithography for the artwork, followed by etching. There are several alternative methods for applying photoresist: spindling the photoresist, spraying on the photoresist, painting on the photoresist, and spreading out the photoresist from a spinner. This relationship between tasks and methods results in a *task network*, part of which is shown in Figure 4.

This decomposition of tasks into various subtasks is important for process planning for the manufacture of microwave T/R modules for two reasons. First, the decomposition in an HTN naturally corresponds to the decomposition of a MIC into the parts and processes required to manufacture it. Second, the ability to include the complex tasks "make drilling and milling features", "make artwork", "assembly and soldering", and "testing and inspection" in sequence provides a uniform framework that can naturally accommodate both mechanical and electronic manufacturing processes.

Sometimes a particular method can always be used to perform a particular task. For example, because spreading out the photoresist from a spinner is so accurate, this method can always be used to perform the task of applying the photoresist. Sometimes a particular method can only sometimes be used to perform a particular task. For example, because spraying on the photoresist is only somewhat accurate, this method cannot be used to apply the photoresist if a coupler in the artwork has a gap of less than or equal to 10 mils.

Certain tasks are *primitive*, meaning that they do not break down into any other tasks. For example, precleaning for the artwork is a primitive task. Once the complex task of making the entire MIC has been broken down into a series of primitive tasks, a process plan has been created; carrying out the steps of the process plan results in the creation of the MIC.

The planning module constructs a set of process plans, and evaluates them to see which takes the least amount of time. In some cases, it evaluates a set of incomplete process plans and discards all but the one which takes the least amount of time. For example, because the method of application for photoresist does not affect the method of application for solder paste, if the quickest method of applying photoresist is spraying it on, then there is no need to generate process plans in which some other method of application is used. If no process plans can manufacture the device—because some manufacturability constraint, such as achievable tolerance, is violated—EDAPS's planner reports the failure and the reason for the failure to the designers.

This generative process planning approach allows us to provide feedback about manufacturability and lead time to the designers, based on actual process plans for the manufacture of the device. Because manufacturing engineers are accustomed to a standard format for the specification of process plans, EDAPS's planner outputs the process plan in this format.

Conclusions

In this paper we have described the process planning module used in the EDAPS system. EDAPS is a design and process planning environment whose goal is to integrate mechanical and electronic design tools in a single platform, and to assist the designers in evaluating designs based on the manufacturing plans. The distinct advantage of such an approach is the ability to evaluate designs from the point of view of the designers and the manufacturers. EDAPS thus highlights a concurrent engineering approach that we have taken to reduce the lead times in electronic manufacturing.

The process planning module of EDAPS has been completed, although its knowledge base is still being tested and fine-tuned. Parts of the rest of EDAPS are still under development. To date, we have completed the routines to extract and store relevant manufacturing information from electronic designs and the routines that build the manufacturing features. Work that remains to be done includes building the routines to generate shape representations of packaged component features in the substrate design module.

Lessons Learned So Far

Process Planning and Manufacturability Analysis. Hierarchical task-network planning appears to be an ideal approach for generative process planning for microwave modules. The decomposition in an HTN naturally corresponds to the decomposition of a microwave integrated circuit into the parts and processes required to manufacture it, and HTNs provide a unified framework that accommodates both electronic and mechanical manufacturing processes.

Although researchers have had great difficulty in developing generative process planners that produce realistic process plans for complex mechanical parts, generative process planning can be more easily applied to microwave T/R modules. In microwave T/R modules, the interactions among mechanical features are much fewer and simpler than the complex geometric interactions that can occur in complex mechanical parts as described in (Nau, Gupta, & Regli 1995).

In applying HTN planning to this problem domain, we found it important to represent the data in such a way as to facilitate integrating the planner with the other EDAPS modules. For example, in order to communicate with the Microstation modeler, the planner needs to access complex geometric information that would be difficult to represent or manipulate as sets of logical atoms as is done in many AI planning systems—so instead, we allow the representation to consist of arbitrary data structures as may be appropriate for the task at hand. This lets us represent the data in a way that is often much simpler than the corresponding logical atoms would be.

Task-Network Decomposition and Total Ordering. HTN planning has long been thought to be more useful in practical planning domains than planning with STRIPS-style operators (Wilkins 1988), and our experience confirms this opinion. Hierarchical planning is also quite natural in process planning for complex electro-mechanical devices, because the planning hierarchy derives naturally from the part-whole hierarchy of the device itself.

However, even though EDAPS's process planning module is an HTN planner, it differs from almost all other HTN planners in that it is a total-order planner. Because its task networks are totally ordered, so are all the plans that it generates. Furthermore, it expands tasks in the order in which they will be achieved: given a sequence of tasks to accomplish, it will always expand whichever task needs to be performed first.

Although this approach may seem quite restricted compared to the partial-order approach used in most HTN planners, our experience suggests that it may actually be the best approach to use in a number of application domains. Not only does it appear to work well in process planning for microwave T/R modules—but as described in (Smith, Nau, & Throop 1996), the same approach (and some of the same code!) also works quite well in another very different application domain: declarer play in the game of contract bridge. That this same set of techniques should have success in two such widely varying areas is quite striking.

In most current AI planning systems, tasks are often expanded in an order other than the order in which they are to be performed. This way, the planner can constrain its search space by making some "important" or "bottleneck" decisions before commiting to other less-important steps. For example, if one wants to fly to another continent, one probably should think about what flight to take before one bothers to develop a complete plan for getting from home to the airport. By looking at the "fly" task before planning every one of the steps that precede it, one can constrain the search space a great deal.

However, planning for a task that will come later in a plan before one has planned everything that will come before them also incurs a drawback: when one is planning for the later task, one cannot know what the task's input state will be, because one does not know what sequence of steps will produce this input state. This fundamental source of uncertainty can make the planning mechanism much more complex than it would be otherwise.

In both of our application domains—process planning for microwave T/R modules, and declarer play in contract bridge—situations can occur where it might be desirable to plan for a later task before planning everything that will precede that task. However, in both domains, such situations do not seem to occur often enough to make it worth the trouble to develop the planning mechanisms needed to do this.

In both of our application domains, planning the tasks in the order that they are to be executed makes it easy for us to use data representations much more flexible than those normally used in AI planning. This makes it much easier to interface the planner to external information sources, and greatly facilitates the task of creating the planner's knowledge base. Both of these activities are crucial for the development of successful planners in realistic application domains.

Plan Explanation. Our generative process planning approach allowed us to provide feedback about manufacturability and lead time to the designers, based on actual process plans for the manufacture of the device. Because manufacturing engineers are accustomed to a standard format for the specification of process plans, EDAPS's planner needed to output the process plan in this format. Adhering to this format required a lot of work.

While this *plan explanation* may seem a small detail—certainly no advanced AI techniques were required—it is a crucial feature of EDAPS's planner. Without EDAPS's plan explanation, its plans would be useless. The issue of plan explanation appears to be important, and we are unaware of any formal approaches to plan explanation.

Future Work

In real life situations, designers never obtain a truly optimum design. A design that is optimal with respect to cost may have poor yields associated with it. In such cases, trade-offs have to be done to attain a design solution that is "somewhat optimal" with respect to all the decision variables.

We plan to incorporate a trade-off analysis module that gives the designers a clearer picture of all the cost versus quality trade-off issues that are involved in each design. To do such trade-off analysis, models to predict yields and costs are needed. To estimate the costs, several formulae are available from standard process handbooks. However, yields are more difficult to predict. The simplest yield model associates a historically determined yield value with each component. In that case, component design features will have quality as an additional attribute. The fundamental assumption with this model is that yields are determined solely by components, and not by the processes involved in the manufacture nor by the designs in which the components appear.

In fact, processes, components, and board design characteristics all determine the yield of the microwave T/R modules. Ball et al. (1995) consider such interactions between processes and parts, and solve the trade-off analysis as an integer-programming problem. However, they require individual process-component yield values as inputs for their models. For new designs, such as the ones we are considering, it is hard to predict such process-component yield values without having subjected the product to several runs in production lines. In the future, we will do further research to determine the yield model most suitable for our application.

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