Research Issues In Process Planning at The National Bureau of Standards

Peter F. Brown
Steven R. Ray

Factory Automation Systems Division
Center for Manufacturing Engineering
National Bureau of Standards
Gaithersburg, MD 20899

Presented By:

Peter F. Brown
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ABSTRACT. Several years ago, the Automated Manufacturing Research Facility (AMRF) project was established at the Gaithersburg site of the National Bureau of Standards (NBS). This facility is unique in several ways: first, all manufacturing activities are under direct computer control; second, all manufacturing data preparation systems and control systems are linked through a complex data administration and communication system; third, all manufacturing operations are carried out by robots and machine tools with a minimum of human intervention. This last constraint requires that all manufacturing data be complete and unambiguous. It was necessary to develop a process planning system which was capable of supporting the particular requirements and manufacturing capabilities of the AMRF. This paper describes the research agenda of NBS and its cooperative efforts over the past few years in the area of Automated Process Planning. Results include: the development of a neutral representation for process plans and a part model; the development of an interactive planning system which supports all controllers in the AMRF hierarchy; the use of expert systems for process and tool selection; automatic speed and feed calculation; and development of a system for automatic part fixturing. The next phase of development involves the introduction of distributed intelligent planning modules. By following a systematic procedure of defining clear interface specifications and establishing a framework for modular software development, progress is being made on the complex problem of process planning in an automated manufacturing environment.

INTRODUCTION. With the rising importance of national industrial competitiveness, the need for technological improvements in the manufacturing arena is becoming acute. It is clear that the source of many of these improvements will be the field of automation. Manufacturing automation can speed product turnaround, reduce the need for retooling, and lead to a more efficient allocation of resources. Automation can be effective for small batch manufacturing and in spare parts production. While this is a desirable goal, many small shops cannot afford to fully automate. By using clearly defined interfaces, a shop can support both manual and automated operations. Pursuing a research agenda for fully automating a factory should yield useful results for manual, semi-automated and fully automated facilities.

There are a number of obstacles to the implementation of a fully integrated automated manufacturing facility. One major gap is the lack of smooth information flow between Computer Aided Design (CAD) systems and Computer Aided Manufacturing (CAM) systems. Traditionally, these two functions have been treated as completely separate activities. There is no feedback from CAM to CAD to reflect the manufacturability of a particular design. There are very few commercial/production systems which actually integrate CAD with CAM. An example of one which does accomplish this for a limited part family is the General Dynamics Advanced Manufacturing System [McMahon87]. After the design of a wing-spar, the design is checked for manufacturability. Potential problem areas are identified to the designer who can then make the appropriate modifications to improve the manufacturing process. The implementation of this system required major modifications to their existing CAD and CAM facilities, and a significant outlay of human and financial resources.

Extending these ideas to general part families is a much more difficult task. A brief example of the information flow illustrates a number of problem areas. A client requests some product to be manufactured and provides a loose set of requirements. This request is translated into a local representation, usually a part drawing. This local representation includes some simple translation of functional attributes into specific tolerance information. The information is loosely organized as notes or text on the part drawing. This step can be done manually or with the current technology of Computer Aided Drafting. The step is complete when the client and designer agree that the drawing adequately represents the client's needs. The problem with this approach is that the information is not represented in a computer database form. This implies that a human will have to interpret the notes sometime later in the process, leading to ambiguities. More importantly, this approach does not allow any feedback to the designer as to the manufacturability of the design.

The next step in the process is to bridge the link to the CAM systems. This is called process planning. Process planning transforms the design information into some local process specification structure used by the manufacturing organization. This step includes defining a group of machinable features and their associated processing steps, selecting target machine tools to be used to process the part, generating tool and fixturing orders, and any other information needed to actually produce the part. The CAM system then expands each process step into more detailed instructions including robot or machine tool N/C programs, tool offsets, etc. It is at this point that important information is generated which should be communicated back to the designer. The important point is to produce a product at minimum cost while retaining the desired quality and functionality.

Thus, the step called process planning is the transformation of information from the CAD representation to the CAM representation. The transformation rules that humans apply are not well understood even by those who use them. Clearly this makes it difficult to encode those rules in process planning systems. It is only when these rules can be represented in automatic systems that any feedback can be given during the design process. To accomplish this, a more powerful product representation is needed. This representation must serve the needs of the designer who is striving for functionality, as well as the manufacturing engineer who wants high quality at low cost.

Key research issues are the development of a complete product definition that captures the design and functional aspects of the part, the understanding and development of the transformation rules discussed above, and finally the development of models of the constraining mechanisms that affect those transformation rules. The key standards issue is the development of a standard process plan representation. A standard representation permits the independent development of planning modules and reduces the integration problem. The process planning project has addressed a number of these issues internally and in collaboration with other organizations. Process planning is one part of the larger AMRF project whose goal is to study the problem of information flow in an automated facility, and to develop and test system interfaces for this information flow.

OVERVIEW. This paper addresses the key research efforts and issues supporting the integration of automated process planning in the Automated Manufacturing Research Facility (AMRF) at the National Bureau of Standards. Section 3 describes the AMRF facility in terms of its goals, architecture and implementation. Section 4 discusses the role of process planning within the AMRF, and identifies some of the underlying issues which must be addressed before integrating a planning system. Section 5 details the research activities supporting process planning conducted at, or in collaboration with, NBS. Section 6 outlines a strategy for future work, and Section 7 summarizes the paper.

THE AMRF. The AMRF was established in 1981 to serve as a testbed facility to support research in measurement techniques and computer interface standards that are required for automated machining of parts in small lot sizes. One of the primary thrusts of the project was to establish clear interface specifications and modular structures to allow plug-compatibility between systems. This allows both a flexible manufacturing environment and offers the capability of incremental automation in existing facilities. Results of this work are already contributing to the formulation of standards for a generic factory model, low level robot interfaces, process plan file structures, N/C machine tool interfaces, communication standards, IGES (Initial Graphical Exchange Specification) and PDES (Product Definition Exchange Specification). Currently, a PDES-like format is used to communicate the part geometry and functionality. As the formal definition of PDES is developed, we intend to maintain compatibility.

(1) **The Role of NBS**. The National Bureau of Standards plays a unique role in manufacturing automation. It serves as a common ground where both academic and industrial research issues can be explored. Industrial research efforts often suffer from the constraints imposed upon them by a plant in full production. The cost of taking down a production line to experiment with new automation concepts is prohibitive. This results in a conservative approach to implementing new technologies in a plant. Universities, while free to take great risks with new ideas, rarely have the resources to carry out large scale experiments involving many industrial robots and controllers. This is primarily due to the large investment in capital equipment that is required. Furthermore, it is difficult to remain aware of the problems currently facing production facilities without either working at such a facility, or working with personnel from the facility. The AMRF addresses many of these problems. Experiments can be carried out on a realistic scale without the loss of production. The AMRF provides a forum where industrial and academic researchers can work and discuss their various perspectives. Finally, by keeping information in the public domain, results of work performed at NBS can be made available to the entire manufacturing community.

(2) **AMRF Architecure**. The AMRF is built around the concept of hierarchical control, where high level commands are decomposed into sequences of simpler commands at the next lower level in the hierarchy, which in turn are decomposed at yet lower levels (Figure 1). Well-defined protocols have been established to allow command and status information to flow up and down the hierarchy. The bulk of data transfer (such as process plans and part models) occurs laterally with a distributed data administration system. A mechanism has been implemented to allow any controller in the AMRF to request or store information in a generic way, regardless of which database is being used to hold that information. The adoption of such an architecture avoids many potential information bottlenecks. Further, by adopting a hierarchical approach, the complexity of a task is reduced to a manageable level for any node in the hierarchy. More details on the AMRF can be found in [Simpson82, Furlani83, Hocken83, McLean83, McLean85, Nanzetta84].

PROCESS PLANNING IN THE AMRF. The process planning system in the AMRF was designed to accomplish many goals. One major goal of the planning effort was to establish a neutral format for a process plan at any level in the control hierarchy. This format had to be simple enough to be easily parsed by the least capable computers in the facility, yet flexible enough to convey complex process plans containing multiple branches. A second goal of the planning system was to serve as a general programming tool for the facility. Since all workstation controllers in the

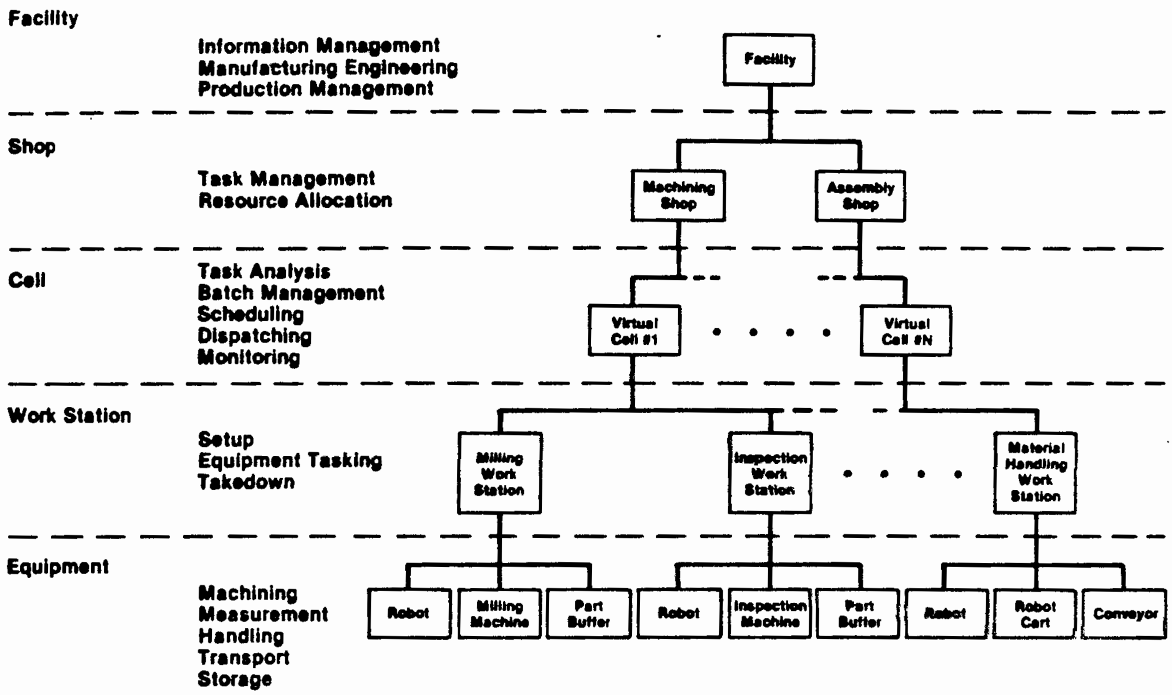

Figure 1. The AMRF COntrol Hierarchy.

facility are designed to interpret and execute process plans in the same format, the process planning system can generate command sequences for activities involving any combination of devices on the factory floor. The planning system supports all three levels of the hierarchy currently implemented: the cell, workstation, and equipment level (Figure 2).

Before these goals could be tackled in a systematic way, a number of issues had to be addressed, for example: What representation scheme should be used for a process plan, both within the planning system computer, and at execution time on the factory floor? How should an individual step within a process plan be represented? How should the hardware and software requirements for a process plan be stored? How is system integration and interface specification to be accomplished? How should the system handle command, status and database transactions, which are common to all systems in the facility? The research program in process planning was formulated with the above questions in mind. The approach used to address these issues, detailed in the following section, was to work on many of the immediate problems within NBS, while supporting and working in collaboration with others on some of the more long term questions. In-house work therefore focussed on representation and interface issues, with outside projects addressing expert system approaches, geometric feature manipulation, automatic fixturing, and other topics.

<u>RESEARCH TOPICS SUPPORTING PROCESS PLANNING IN THE AMRF</u>. A technology evaluation was carried out early in the project to determine the current state of the art of both production and research process planning systems. The goal was to determine if the technology used in these systems could be used in a facility such as the AMRF, i.e. one with direct computer control of all factory operations. It was found that variant planning systems suffered from severe drawbacks in generality and extendability, and no system addressed all the necessary issues. It was further decided that a number of central items had to be developed which simply did not yet exist. These included:

- A standard representation of process plans based on programming language theory from computer science.

- A standard representation of activities on the shop floor. A representation was derived based on knowledge representation techniques from artificial intelligence.

- A product representation (rather than just a part drawing) as output from a design system. This representation is used to drive the planning system.

- A methodology to allow the generation of alternate functional views of the product data as needed by various factory systems.

- A methodology relating these features to the automatic generation of machine specific code.

This section describes the research performed at NBS and elsewhere in collaboration with the AMRF, dealing with issues such as those outlined above. The interactive planning framework built to support the AMRF is also reported.

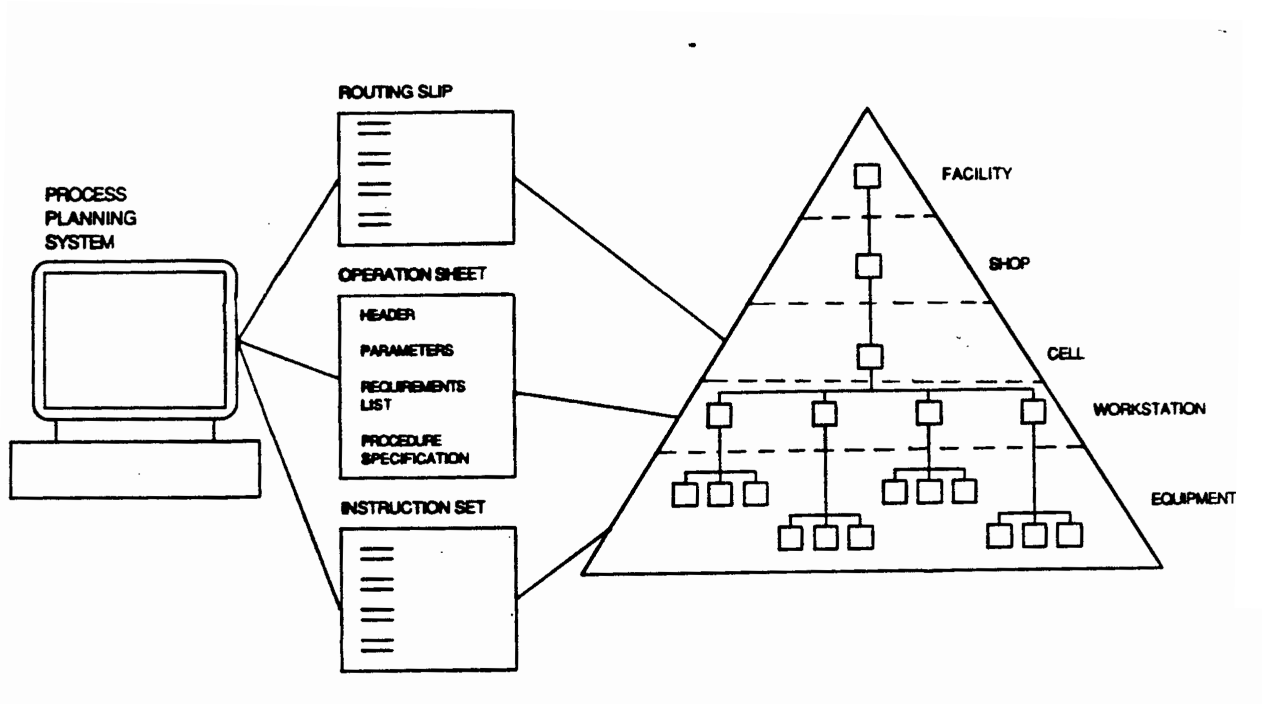

Figure 2. Process planning data packets and corresponding control levels.

(1) Assessment of Computer-Aided Process Planning. Two key collaborators working with NBS on the early phase of research into computer aided process planning were Dr. Ted Chang and Dr. Dana Nau. An NBS grant to Dr. Richard Wysk at Virginia Polytechnic Institute entitled "Advances in Computer-Aided Process Planning", [Chang83] provided a useful survey of existing planning systems and current concepts. The outcome of this work served as the basis of the book "An Introduction to Automated Process Planning Systems" [Chang85]. At the same time, Dr. Nau was at NBS as a guest researcher who became interested in the applicability of artificial intelligence to process planning. The result of his work was "Expert Computer Systems and Their Applicability to Automated Manufacturing" [Nau82]. Many of our current concepts on process planning came out of this early collaboration.

(2) A Machine Tool Planner for Automated Process Planning. A core task in the transformation of design data into a process plan is the task of process selection, followed by machine code generation. Typically, this means starting with the specification of a design and determining the processing step or steps needed to produce it. In collaboration with the University of Kansas, a graduate research project began at NBS [Hummel85] to investigate possible means of performing such a task automatically. One of the outcomes of the investigation was the decomposition of the task into three parts. The three parts or phases are called: feature planning, operation planning and machine planning. During each of these phases "constraint posting" is used, constraint posting consists of the formulation, propagation and satisfaction of constraints which describe the interactions between various sub-problems. The constraints can, for example, include causal relationships between machining operations, or restrictions on resources. The first step (feature planning) takes a list of manufacturing features as input. If no processing knowledge exists for a given feature it is decomposed into a list of simpler features, by means of pointers embedded in the feature definition. This could lead to the generation of precedence constraints based on the sub-features produced. The next step, operation planning, involves the selection of machining operations to produce each of the "elemental" features identified in the previous phase. The machining operation specifies various parameters, such as feed rate and cutter speed. Finally, the machine planning step turns these operations into groups of APT-like program segments.

The Kansas implementation uses a production rule approach, modeled after conventions of YAPS [Allen83], to represent the rules needed in each of the planning sub-tasks. The system is written in Franz Lisp (tm) on a Sun Microsystems workstation, specifically for a Bridgeport CNC vertical milling machine. It has successfully produced plans for a limited set of pocket and hole making operations. Mr. Hummel has continued this work at the Bendix Corporation. Concepts such as meta-rules to control the search, and an optimum search tree generator have been implemented. A simple geometric reasoning capability was also added to aid in the feature decomposition problem. Much was learned about the representation of machinable features and the need for better geometric reasoning capabilities and constraint propagation methods.

(3) Automated Process and Tool Selection. Several years ago, an independent effort was initiated at the University of Maryland by Dr. Dana Nau to investigate novel approaches to the application of artificial intelligence to process planning. This work was funded in part by NBS. Dr. Nau developed a prototype reasoning system in Prolog called SIPP (Semi Intelligent Process Planner). This was soon followed by a version implemented in Franz Lisp , then re-coded in Zetalisp on a

Symbolics Lisp machine. Dr. Nau realized that a core task in the planning problem was that of selecting a process, given an isolated manufacturing feature. The latest version focused on this problem, and was named SIPS (Semi Intelligent Process Selector). SIPS is a frame-based reasoning system which was designed around the concept of "hierarchical knowledge clustering", [Nau87].

There are several advantages to the SIPS approach as compared to traditional production rule systems. First, conditions which are common to several processes can be evaluated in a parent node. Thus, only the conditions which distinguish one process from another "sibling" process need be evaluated by any of the child nodes. The second major difference is the concept of the cost of a process. Ideally, one would like a process selector to generate a plan with the lowest cost. In production rule systems, priorities can be assigned to rules which rank them by cost, but generally the priorities must be assigned beforehand. In SIPS, the order of the search is determined by the cost estimate for each process, which is calculated during the reasoning process. Thus, in situations where the cost is feature dependent, SIPS offers a convenient way to rank the candidate processes. Finally, SIPS provides a representation of both procedural and declarative knowledge in a conceptual frame.

The SIPS system is currently integrated into the interactive process planning framework of the AMRF. It can be invoked when editing process plans at the equipment level of the hierarchy. In operation, the process engineer specifies the part to be machined in terms of design or manufacturing features meaningful to SIPS, ordered in a feature graph. Each feature can then be passed to SIPS, which will replace that feature in the graph with the process, or sequence of processes recommended to produce it. It is then the task of the engineer to consolidate the collection of processes needed for all the features into an optimized sequence of operations. The optimization of this last step is currently being investigated. Enhancements to SIPS are currently being supported, through cooperative research efforts between NBS, Dr. Nau and researchers from Texas Instruments. These efforts involve the enhancement of: 1) the overall problem solving paradigm, 2) the inferencing strategies used, 3) the knowledge representations employed, and 4) the domain specific knowledge bases.

(4) <u>Automated Fixturing - University of Kansas</u>. The Department of Mechanical Engineering at Kansas University has been working with NBS under a grant for several years on computer integrated manufacturing. One research issue has been in the area of automated part fixturing, [Carlyle86]. This process is almost always performed by a machinist because of the complex nature of the problem. Researchers at Kansas believed a properly designed modular fixturing system could be assembled by a robot. By constraining the range of solutions using modular fixtures, progress could be made in developing an automated approach to part fixturing.

Work proceeded along three main branches: to develop fixturing hardware to be controlled by computer, a fixture planner, and a robot planner. The fixturing hardware was designed to be a baseplate type of assembly, with a matrix of conical holes. Each hole accepts an endstop or a clamp. Further, the clamp can then be driven hydraulically under computer control to open or close. To support the hardware, a fixture planner was also developed, called "Baseplatetool", [Unger86]. This system graphically displays the baseplate on a computer screen, and allows a process engineer to specify the arrangement of stops and clamps needed for a fixturing operation. The system uses a two dimensional modeler for the purposes of speed, unlike an earlier version which used a solid modeler. An important feature of the system is the use of a separate database to store all facility-dependent information. This includes the layout of the baseplate itself, the clamp designs, the parts to be fixtured, the locators used, the size of the locator holes, etc. In this way, Baseplatetool can be quickly adapted for use with any hole-based fixturing system. The interface uses mouse input. Great efforts were made to allow the engineer to remain at the conceptual level when designing a fixture. The third development was a robot planner to allow robotic assembly of fixtures. This system takes the fixture design generated using Baseplatetool, and produces a process plan to be used by a robot in the assembly of the fixture components.

To integrate the work on automated fixturing with the ongoing research at NBS, a postprocessor was written for the robot planner. This produces a process plan in the neutral AMRF format for the robotic assembly of a fixture designed with the tool. The fact that the fixturing hardware and software was fully integrated with the AMRF within a week of its arrival at NBS serves as a testament to the power of machine independent interfaces.

(5) <u>AMRF Process Planning System</u>. The process planning system consists of two primary sections: a configuration tool and editing tools, (Figure 3). The configuration tool is used to specify the organization of the equipment on the factory floor. Thus, it allows a user of the planning system to construct a representation of the facility. This representation contains the cells, the machining and support workstations, and all of the associated processing equipment.

An internal database is used to keep track of the activities or functions that each factory floor system can perform. The database maintains the specification of an activity, its associated constraints and other information. These activities are called work elements, [Ray86]. The work element concept is derived from the idea of an operator in state space. Thus, the application of a work element results in a transition within a control system from one state to another. From the perspective of the planning system, every control module in the factory is treated the same way, whether it controls equipment (such as a machine tool controller) or directs other control modules (such as the cell or workstation controllers).

The second tool is the one used to actually create, edit, or view process plans. The plans created with this tool are in terms of the entities and work elements defined in the configuration tool. There is a network interface to external databases where process plans can be stored, and other information such as part models and inventory data can be accessed. Once the user has selected a process plan for editing, the information can be displayed in two alternate forms. One

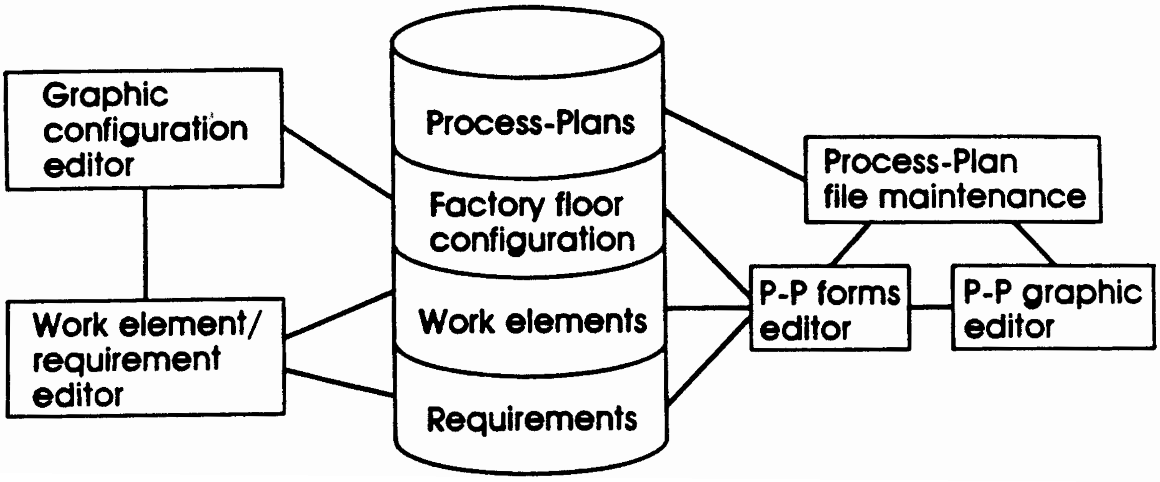

Figure 3. The AMRF Process Planning System.

display uses a text or form layout, while the second uses a graphical representation based on the precedence information within the plan. Both tools show the same information, but the graphical tool provides easier viewing of the overall plan while the textual display gives the user more detailed information.

A major effort supporting the integration of the planning system within the AMRF was the development of a neutral process plan format. This format is an ASCII based language specification that is used throughout the AMRF. A process plan is comprised of four major sections:

1) Descriptive Header - contains static index and summary data.
2) Parameters - lists all variables for which real values must be substituted at execution time.
3) Requirements List - identifies all resources to be used during the execution of the plan.
4) Procedure Specification - describes all work elements, their precedence *relationships*, their attributes and specific value bindings.

Further details of the interactive process planning system can be found in [Brown86].

Another critical interface developed within the AMRF is a part model or product specification format. This part model consists of the part geometry and topology (based on a boundary representation) and part functionality, [Hopp87, Tu87]. The functionality section allows the specification of datums, datum reference frames and tolerance information. In addition to this information, a mechanism has been developed for the specification of features. These features can refer to any information within the part model, including other features. This format provides a mechanism which allows multiple uses of the part model (such as design, process planning, vision, and inspection). An application system use the same underlying part specification, but develops different views of this information.

In summary, the current planning system supports the neutral process plan format and the part model format. Process plan procedures are described in terms of work elements. The system also has the capability to invoke an external expert module to perform automated process selection. The neutral process plans are readable by all controllers within the AMRF. Some of the equipment controllers then execute predefined N/C programs. The vertical machining workstation can dynamically generate N/C code from a process plan and feature description, [Kramer86].

STRATEGY FOR FUTURE WORK. The major goal during the first several years of the AMRF was the design, construction and integration of the present facility. That goal has been reached and the system was demonstrated during the public test run in December of 1986. The next phase of research is to conduct experiments using the current facility. One important research area is the development of distributed planning and control systems.

(1) Perspective of Current Work. The current implementation of the process planning system supports the architecture of the AMRF. This system is interactive, i.e. it requires human decision making throughout the development of a process plan. The system was designed to allow modular extensions for intelligent problem solving. The SIPS system has been integrated and other expert modules can be added in a straightforward manner. This is possible because of the fundamental work already done in designing the interfaces to the AMRF.

One of the key outcomes of the work done to date has been the rethinking of the role of process planning in an automated factory. Also, the importance of clear, well defined interfaces cannot be over-emphasized. The development of standard interfaces has been of great help in speeding the software development. A great deal of work still needs to be done to define interactions between control systems and planning systems and refine the features used in the product specification.

With a framework in place which supports process planning in a fully automated environment, work can now proceed on the integration of artificial intelligence technology into the system. By proceeding in this way, we hope to keep our efforts focused on those areas most needing attention.

(2) Role of expert systems and artificial intelligence. It is clear that expert systems have a vital role to play in the manufacturing environment. Many portions of the manufacturing decision making process are based on heuristic rather than algorithmic knowledge. Some key areas are ripe for consideration for future expert systems, such as resource allocation, machine selection, tool selection, etc. Tying all of these systems together into a series of cooperative expert systems still remains one of the most important challenges. At the same time, however, the need to better integrate conventional programming tools with the current system has become apparent. Many relatively straightforward tasks still need to be performed, such as data base interfaces and speed/feed calculations. Tasks which do lend themselves to expert system solutions may still be best accomplished with computer-assisted tools which interact with a human engineer. The computer-assisted tools will probably have the largest immediate impact in the manufacturing arena.

(3) Distributed, Real-Time Planning. A distributed architecture offers the greatest chance of success for the implementation of a flexible planning system which can react in real time to unforseen situations. The AMRF hierarchical control architecture is a convenient testbed in which to develop these planning concepts. The hierarchical approach means that a complex problem can be broken down into a number of solvable sub-problems [Sacerdoti77]. By distributing the problem among a number of processors, more computational resources can be applied to the problem in parallel. Further, the modular construction allows the system to be easily modified to reflect changing factory configurations. Figure 4 shows the allocation of planning responsibility among a level hierarchy. Figure 5 represents a hypothetical scenario for information flow between two levels within the hierarchy. Each node has both a planning and control module. What follows is one example of how a distributed planning and control system could function.

- The control level Z passes down a command for a job to be performed.

- The A planner might already have a stored template describing the appropriate course of action, or it could develop a set of tasks necessary to execute the command.

- Planner A asks the subordinate level planners about the feasibility of sub-tasks X,Y,Z...

- Planner B responds with a "YES" and returns a process plan that includes an estimate of the time, cost and resources required.

- Planner C supports a similar piece of equipment and also returns "YES" with a lower cost, but a much longer time estimate.

- This information is then used by the planner or controller at level A to decide which plan would be best to use, and to combine and optimize the various sub-tasks.

At a given time, module C could be a better choice, but some time later, if delivery time became critical, module B would be a better choice. Further, if module C should break down during execution, the planner could simply recommend module B as an alternative. It is important that a planning module first produce a rough estimate as to whether it can handle a job, and then during execution help provide error recovery. This second step could be performed by continually generating contingency plans, whenever the module is otherwise idle.

There are of course numerous ways that a cooperative planning and control architecture could be designed, this represents just one approach. It is our belief that the architecture of the AMRF, and the interfaces that have been defined will allow the implementation and testing of these ideas in a convenient and robust fashion.

Planning Levels	Planning Functions
Level 1	GT-Cell Classification
Level 2	Machinable Feature Classification Plan Optimization
Level 3	Process Selection Tool Selection

Figure 4. The decomposition of planning functions within a hierarchical planning system.

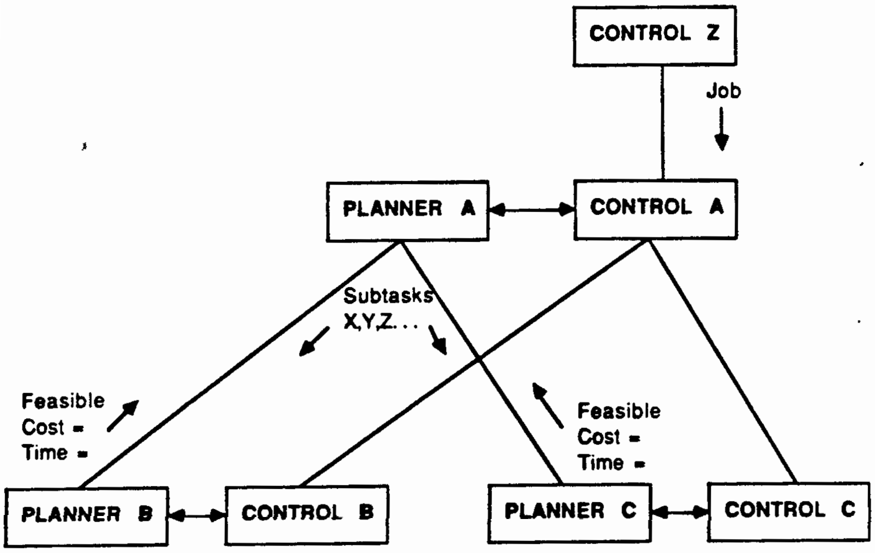

Figure 5. Flow of planning information within a distributed hierarchical planning system.

(4) Portability. The current process planning system was written in Zetalisp running on a Symbolics computer system. We still feel Lisp is the best environment for this type of software because it is widely available, it supports object oriented programming, windowing facilities, flexible data typing and an interactive programming environment. All of these features greatly enhance the productivity and flexibility of a software developer. But issues have emerged concerning the differing needs of software development environments and application delivery systems. Since we started the process planning system, general interest in artificial intelligence environments has greatly increased. The Lisp environment on conventional computers has improved significantly. Personal computers have now become serious Lisp programming tools.

We are beginning to define the environment for the distributed planning system. We are looking into a Lisp environment which contains portable, public-domain software. This software should include object-oriented and windowing facilities. Our goal is to be able to implement a system which will run on a variety of host machines.

(5) Design by Features.
In traditional design, the functionality of a part is never explicitly stated. The designer transforms the functionality into geometry and tolerance specifications. Subsequently, there is no good way to provide feedback to the designer on issues such as cost, manufacturability and performance. An important development which should radically change this situation is the concept of design by features. Since both designers and process engineers conceptualize in terms of features, a feature representation is a natural vehicle for part description, [Dixon86, Hummel86]. We believe that a relationship can be established between design and manufacturing features. Once this relationship is known, a mechanism can be developed to provide the feedback to the designer. Default parameters can also be attached to these features, making the design and manufacturing tasks more consistent. In this way, the risk of over or under-constraining a design is reduced. Finally, these features can be related directly to geometry to aid in the analysis of the functionality of a part, such as strength, heat transfer characteristics, etc. This approach underscores the fact that manufacturing concerns are as important as functionality in order to produce economical, high quality products. All aspects of a part, including design, analysis, manufacturing and inspection should be weighed against one another.

CONCLUSIONS. The Automated Manufacturing Research Facility at the National Bureau of Standards is pursuing a systematic approach to the development of process planning systems for future automated factories. Early work focused on representation issues. Results include a neutral process plan format, a part model format, and the concept of a work element. Building on this framework, an interactive planning system was designed and implemented. The system provides planning service for all AMRF control systems. As work progressed, we learned more about how an intelligent planning system should interact with intelligent control systems. With the integration of expert planning modules, we are now ready to proceed toward the design of a distributed, hierarchical planning system.

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