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Supervisory Planning in DPP

Lihui Wang
Ningxu Cai
Hsi-Yung Feng

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Supervisory Planning in DPP

Submitted by
Présenté par
Group Leader

First Author
Auteur Premier
Lihui Wang

Approved
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EXECUTIVE SUMMARY

As decentralization of business grows, manufacturing shop floors are requiring dynamic process planning capabilities that are responsive and adaptive to unpredictable changes of distributed production capacity and functionality. To meet the requirement, a novel methodology of distributed process planning (DPP), comprising supervisory planning and operation planning, is proposed to achieve dynamism and flexibility of process plans.

As a crucial constituent component within DPP, the supervisory planning is responsible for generating manufacturing resource-independent process plans at the shop floor level. The input of supervisory planning is product data after feature recognition, and the output of it is properly sequenced machining features with embedded tool type, tool path generation logic and fixturing information, which are grouped into different setups and encapsulated into function blocks. A network of such function blocks will be dispatched to a selected machine in the shop floor for low-level operation planning.

This report focuses mainly on functional analysis and task description of each module of supervisory planning. The reasoning and decision-making in supervisory planning are machining feature based. They are modularized into four parts for machining feature parsing, machining feature-based sequence generation, function block design and agent-based execution control, respectively. Enabled by the DPP and machining feature-based reasoning approach, the high-level process plans become generic and open, with increased flexibility and dynamism.

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1 INTRODUCTION

Process planning is a task of translating a set of design requirements and specifications into a set of technologically feasible instructions describing how to manufacture a part. To perform the process planning task, various skills are required from process planners. Some of these are the ability to analyze the requirements for producing parts and the ability to understand the interactions among various aspects such as quality and cost, extensive knowledge of machine tools, cutting tools and their capabilities. However, various process planners' judgments and experiences can lead to the differences in the perception of what constitutes the optimal way of production. Maintaining the consistency of all process plans and keeping them optimized could be a difficult task. This is one of the main reasons for the development of computer-aided process planning (CAPP) systems that attempt to support process planners in planning processes and making decisions [1].

In the last decade, the change in market requirements towards a larger variety of products in smaller batch size has led to the concept of next generation reconfigurable manufacturing systems (RMS) being an integrated network of distributed resources simultaneously capable of combined knowledge processing and material processing. RMS is a manufacturing system which can be created by incorporating basic process modules, both hardware and software, that can be rearranged or replaced quickly and reliably [2]. It will allow flexibility not only in producing a variety of parts, but also in changing the system itself. It is required to be agile and fault-tolerant, and will contain collaborative and intelligent entities that can dynamically adjust themselves so as to achieve a global system objective. The dynamic environment of an RMS characterized above requires creating an intelligent and dynamic process planning system that is responsive and adaptive to unpredictable changes of distributed production capacity and functionality. Most CAPP systems available today are centralized in architecture, vertical in sequence, and off-line in knowledge processing. It is difficult for those traditional CAPP systems to deal with dynamic situations (e.g. product changeover, job delay, unavailable fixture, tool or machine breakdown.) regularly happening in today's machining shop floors.

Aiming at the emerging RMS paradigm, a novel adaptive and distributed process planning approach – Distributed Process Planning (DPP) was proposed by Wang and Feng to improve the flexibility and dynamism of process plans [3]. Different from conventional methods, the proposed methodology uses a two-level structure: shop-level supervisory planning and CNC controller-level operation planning to deal with generic data and machine-specific data, respectively. The former concentrates on the product data analysis, machining sequence generation and machine tool selection, while the latter focuses on the detailed working steps including cutting tool selection, cutting condition generation, and tool path planning. As the controller is knowledgeable of the capability and run-time status of the machine being controlled, it is possible to reach local optima for machining without affecting other tasks. It is also expected that the new approach can improve the performance of shop floor operations.

Within the context of DPP, this report focuses on architecture design and task modularization of the generic supervisory planning. First, a brief review of related work is presented in Section 2, and then the fundamentals of entire distributed process planning system are briefly explained in Section 3. The problems about machine-independent planning are discussed and further detailed system architecture of supervisory planning is given in Section 4. The task description of each module of supervisory planning is investigated in Sections 5. Finally, Section 6 concludes that the generic sequence generation can save the time and effort for process plan generation, and shows promise of increasing the flexibility and dynamism of process plans in a dynamic shop floor environment.

2 LITERATURE REVIEW

From design to manufacturing of a mechanical product, a number of steps must be followed, such as design data analysis, process selection and sequencing, cutting tool selection, tool path planning, operation optimization, NC data generation, as well as fixture design and set-up planning. These preparatory tasks are generally referred to as process planning. Research on process planning has been a hot topic for decades. In spite of the benefits promised by the various developed CAPP systems, their adoption by industry is still painfully slow. Today, shop floor engineers and operators still have to meet and respond the challenges for producing highly complex products, especially in very small batches. An efficient adaptive process planning system is thus required to address the shop floor dynamism and to improve the shop productivity.

Since 1965 when Niebel reported the idea of using the power of computers to assist the process planning [4], subsequent researches have been numerous and active. Until 1989, more than 156 CAPP systems have been reported and summarized by Alting and Zhang in their literature survey [5]. Many papers have been published in this area during the last three decades [6]. Most of the papers appear to introduce only specific CAPP systems, although a few papers give a general survey [5-11].

2.1 Approaches to CAPP

There are generally two approaches to CAPP systems, namely the variant and the generative. The variant approach was used in early computer-aided process planning systems, and is basically a computerized database retrieval and editing approach. The variant approach is based on group technology methods of classifying and coding parts for the purpose of segregating these parts into family groups. In this approach, parts produced in a plant are grouped into part families, distinguished according to their manufacturing characteristics. For each part family, a standard process plan is established. The plan is stored in a computer file and then retrieved for new parts that belong to that family. Some form of parts classification and coding system is required to organize parts into families for correct retrieval of an appropriate plan for a new part. A major problem with this approach is the lack of adequate classification models that can provide consistency in classifying and coding parts. It is also restrictive in that new parts to be planned have to be those already in the data file. The quality of the process plan still depends on the knowledge background of a process planner [6]. The first and also most widely used CAPP system, with the same acronym but for CAM-I's Automated Process Planning system, was developed with variant approach in 1976 under the direction and sponsorship of CAM-I (Computer Aided Manufacturing – International) [12]. In the same year, another variant CAPP system called MIPLAN was developed by OIR (Organization of Industrial Research) [13].

The second approach to CAPP is the generative type that partially or automatically generates a process plan according to a product's features and its manufacturing requirements based on knowledge. Systems of this type synthesize a new process plan for each specific part, based on an analysis of part geometry, material and other factors that may influence manufacturing decisions. Inputs to the system would usually include a comprehensive description of the part. This may also involve the use of some form of part coding, but this does not involve the retrieval of existing standard plans. These systems usually employ either a set of algorithms or knowledge-based techniques to progress through the various technical and logical decisions toward an appropriate process plan for a part. The generative approach provides fast advice to designers early in the design process and is closely coupled with the product-modeling activities. The major advantages of this approach are consistency and automation. Once the manufacturing technology, and type of process equipment have been chosen, further detailed planning is carried out as usual [6]. Several well-known generative CAPP systems are APPAS [14], CMPP [15], XPLAN [16], K-Base [17]. Statistics of existing CAPP systems shows that most researchers adopted the generative approach in the development of new CAPP systems.

Meanwhile, with the rapid development of new techniques, many CAPP systems do not exactly fit the classification of variant and generative; they combine other techniques or combine both approaches. Among previous researches, studies on process planning include object-oriented techniques [18-20], GA-based techniques [21][22], neural network-based techniques [23][24], Petri net-based techniques [25], feature recognitions [26-31] or feature-driven techniques [33][34], knowledge-based techniques [18][34-39], web-based techniques [40][41], and agent-based techniques [42-49]. These approaches, techniques, and their combinations have been applied to various specific problem domains, such as tool selection [50-56], tool path planning [57-59], machining parameters selection [53][60], process sequencing [29][61-62], and set-up planning [63][64]. The appendix summarizes the latest developments in the area of CAPP. The listing consists of the name of the system or tool, research group and its reference, key features, and application domain [65-72]. The use of knowledge-based systems and artificial intelligence (AI) techniques is evident in most CAPP systems. Some details to certain approaches are given below.

As decentralization of business grows, research focus of process planning is recently moving towards solving problems in distributed manufacturing environments. Tu et al. introduced a method called IPP (incremental process planning) for one-of-a-kind production (OKP) [66]. The IPP approach is used to extend or modify a primitive plan (a skeletal process plan) incrementally, according to the new features that are identified from a product design until no more new features can be found. A complete process plan generated by the IPP may include alternative processes. This means that a given part can also be processed by alternative machines in alternative sequences in a different plant.

Such kind of distributed manufacturing environment also changes the way of applying AI techniques to process planning. In addition to centralized AI approaches (e.g. genetic algorithms, neural networks, fuzzy logic, knowledge-based or expert systems, etc.), agent technology being one type of distributed AI approaches has attracted wide attentions. Instead of being one large expert system, cooperative intelligent agents are being used in developing distributed CAPP systems. CoCAPP (Cooperative Computer-

Aided Process Planning) [45] attempted to distribute complex process planning activities to multiple specialized problem solvers and to coordinate them to solve complex problems. Also, it tried to satisfy five major requirements: autonomy, flexibility, interoperability, modularity, and scalability. It utilizes cooperation and coordination mechanisms built into distributed agents with their own expert systems. Each agent in the system deals with a relatively independent domain of process planning. Collectively, multiple agents can solve complex problems.

Shih and Srihari proposed a distributed AI-based framework for process planning [46]. Their approach decomposes the entire production control task into several subtasks, each of which is implemented by an intelligent agent. By working collectively, the agents can arrive at a solution for the problem. Similarly, Sluga et al. introduced a VWS (virtual work system) [47] as the essential building block for decision-making in a distributed manufacturing environment. The VWS represents a manufacturing work system in the information space, and is structured as an autonomous agent. It is a constituent entity of an agent network in which dynamic clusters of cooperating agents are solving manufacturing problems. The decision-making in process planning is based on a market mechanism consisting of bidding-negotiation-contracting phases. The VWS approach aims at enabling dynamic decision-making based on the actual state of a given environment.

CyberCut is a research project that aims to develop a networked manufacturing service for rapid part design and fabrication on the Internet [40]. A critical part of this service is an automated process planning module that is capable of generating process plans to satisfy the desired geometries and specified requirements. Three types of agents are designed to facilitate the CyberCut: primary process planning agent, environmental planning agent, and burr minimization tool path planning agent [49]]. The multi-agent planning module incorporates conventional and specialized planning agents for environmental consideration and burr minimization. However, the interactions between those agents are based on human decisions.

Despite the achievements of those CAPP systems, their ability to generate a new plan for the specific part or recognize design specifications and distinguish whether existing process plans suit a new workpiece is still weak. This may be due to centralized architecture, feature-modeling deficiency, off-line knowledge processing, insufficient knowledge bases and lack of adaptive-learning and decision-making capability.

2.2 Future Trends

The following are some future trends in CAPP suggested by researchers in this field [6][11].

- Architecture and constraints for machining operations should be considered for different manufacturing environment while developing a CAPP system. A trend is evolving for distributed and more decentralized process planning systems.
- Process planning needs to be integrated with production planning and control, and to be enhanced to consider the shop floor status, making it a truly real-time and dynamic process planning.

- Process planning research should focus on pre-existing feature precedence hierarchies instead of adopting variant/group technology part family or rule-based expert system strategies.
- The feature-based modeling deficiency should be overcome so that a user can interactively identify complex features from basic geometrical features and entities.
- CAPP should be integrated with product design in terms of design for manufacturing.
- Knowledge-based systems for CAPP should be developed for realizing integrated and intelligent process planning systems.
- Intelligent CAPP will play an important role in modern manufacturing industry. One important feature of intelligent CAPP is the better performance in coping with the uncertain nature of shop floors.

3 FUNDAMENTALS OF DPP

Reconfigurability is an important issue in today's shop floors. Traditionally, process planning is separated from production control and scheduling by bold borderlines. As a result, information about capability and current load of resources as well as further economic aspects remain disregarded. These kinds of CAPP systems are weak in handling unexpected events like machine breakdown, missing devices or tools etc. Generally, complexity of manufacturing process and the knowledge required for process planning increase proportionally. On the other hand, due to the lack of knowledge exchange, quality and reliability of planning results will be reduced on a long-term basis [73]. In dynamic shop floors, a process plan that is generated for a specific machine may have to be regenerated when the status of the machine changes. There is an increasing need to develop a new approach to address these issues. The concept of DPP (Distributed Process Planning) is thus developed for this purpose [3].

3.1 Two-Level Structure

A process plan generally consists of two parts: generic data (machining method, resource-independent machining sequence, and suggested machine tool or cutting tool type information) and machine-specific data (cutting tool ID and parameters, cutting conditions, and tool paths). A two-level hierarchy is considered suitable to separate the generic data from those machine-specific data in distributed process planning as shown in Figure 1.

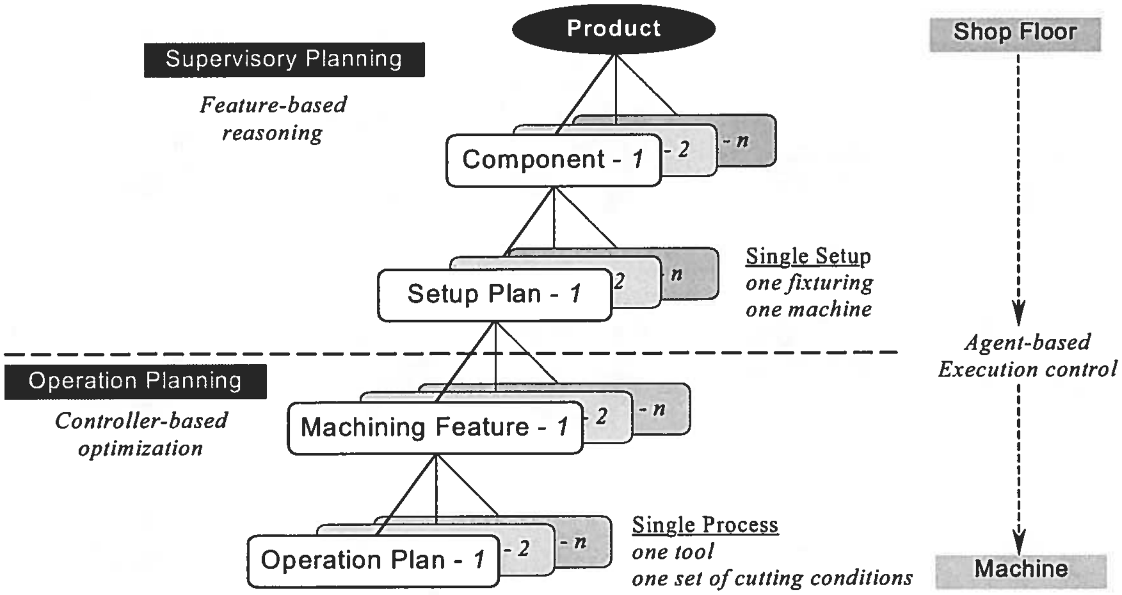

Figure 1. Two-level structure

The tasks of DPP can be divided into two groups and accomplished at two different levels: shop-level supervisory planning and CNC controller-level operation planning.

The former focuses on product data analysis, machining feature decomposition, setup planning, machining process sequencing, and machine selection. The latter considers the detailed working steps for each machining operations within each setup, including cutting tool selection, cutting condition assignment, tool path planning, and control code generation. Supervisory planning is based on the information extracted from design data and manufacturing knowledge. It is relatively generic and needs to be done only once. Operation planning is accomplished at run time by open architecture CNC controllers based on the capacity and real-time status of machines.

3.2 Enabling Technologies

There are three key enabling technologies used in DPP: machining features, agent technology and function blocks.

3.2.1 Machining features

Machining features are used as information carriers from product design to NC machining in DPP. Machining features are those shapes, such as step, slot, pocket, and hole, which can be easily achieved by the available resources and defined machining technologies. Different from design features, as standard shapes that can be machined, each machining feature holds a set of loosely coupled information about how to fabricate it, such as cutting tool type, machine-independent machining sequence, tool path generation logic, and cutting strategy, which provide an indication as to what kind of operation and tools will be required to manufacture the feature. Some typical machining features are shown in Figure 2.

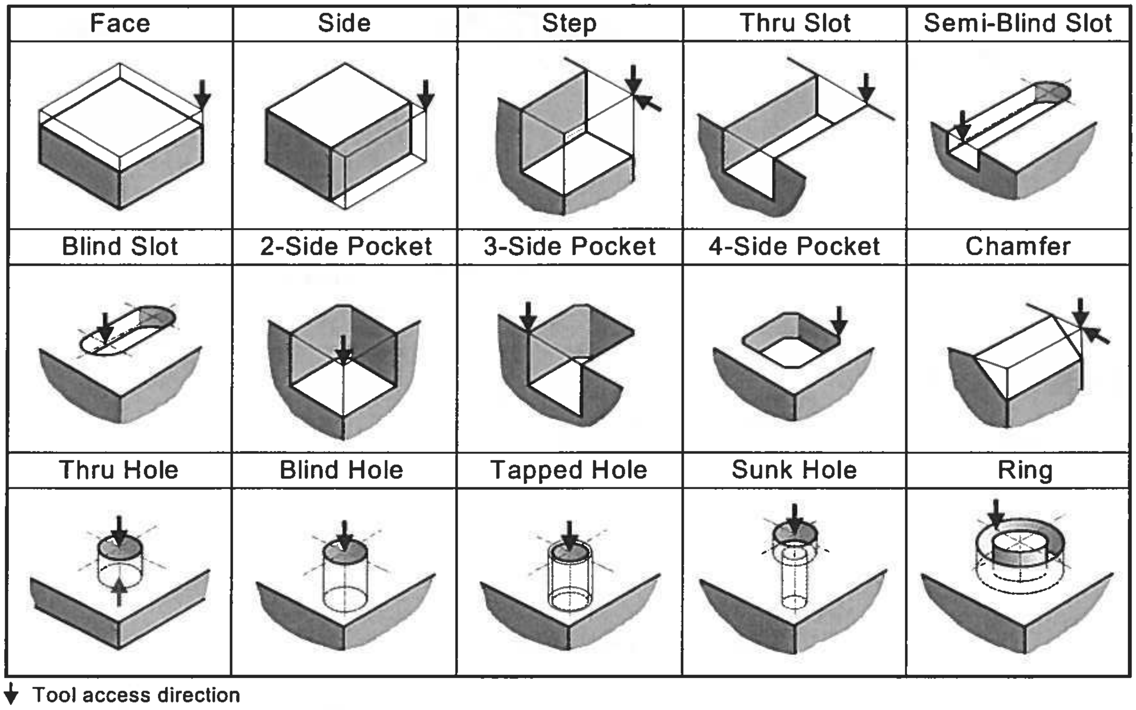

Figure 2. Typical machining features used in DPP

By using the machining features as information carriers, the time and efforts spent in subsequent processes (e.g. process planning, tool selection, operation optimization, and NC code generation, etc.) can be significantly reduced. As illustrated in Figure 3, machining features are used in the DPP for information retrieval, data exchange, and decision-making support at different stages.

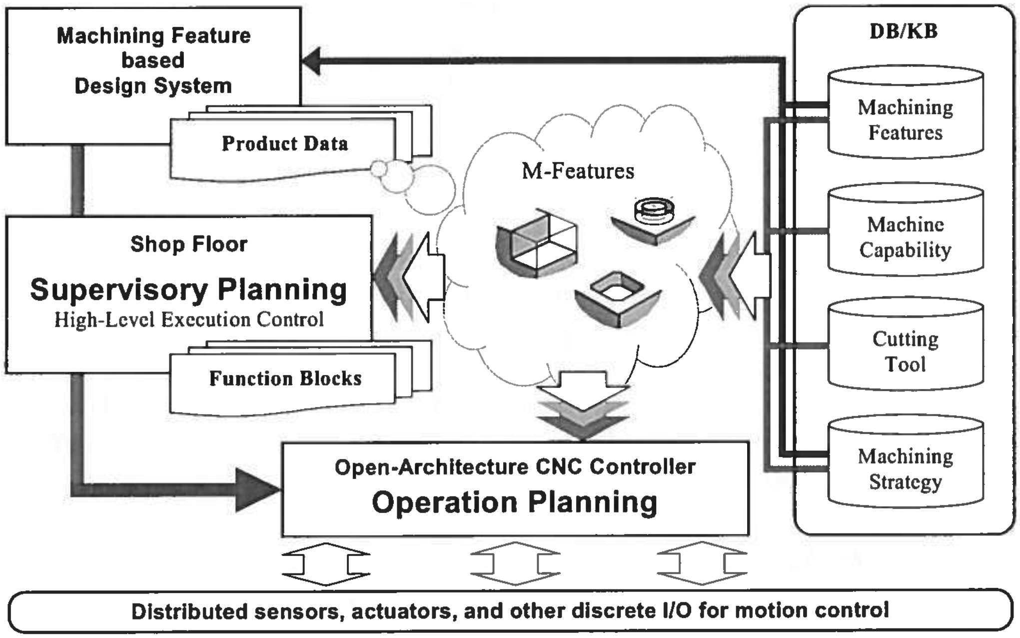

Figure 3. Machining features used as information carriers in DPP

3.2.2 *Agent technology*

A common definition of agents is that agents are active, persistent (software) components that perceive, reason, act, and communicate. Some researchers add further features, such as autonomous, reactive, pro-active, deliberative, adaptive, mobile. Figure 4 shows the agent architecture developed in DIDE project [74]. A DIDE agent is composed of a network interface, a communication interface, local knowledge, internal knowledge base and agent models.

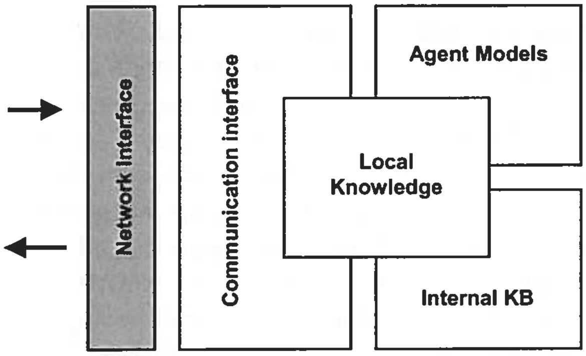

Figure 4. Architecture of a DIDE agent

Although, in many cases, agents can act separately to solve a particular problem, it often happens that a complete system made of several different agents has to be designed to cope with a complex problem involving either distributed data, knowledge, or control. A multi-agent system can therefore be defined as a collection of, possibly heterogeneous and loosely coupled, computational entities, that are knowledgeable in their local domain, have their own problem-solving capabilities, and are able to interact in order to reach an overall goal. In the past ten years, the developments in multi-agent systems in the domain of distributed artificial intelligence have brought new and interesting possibilities for intelligent manufacturing. For efficient use of manufacturing resources and increased flexibility, it is necessary to migrate a CAPP package into a distributed information processing system in which entities can work cooperatively towards overall system goals. This requires distributed parallel computation, asynchronous process coordination, and standard communication protocol. Such a planning system can be readily realized through the multi-agent paradigm, where agents can be used to encapsulate existing software systems, represent manufacturing resources and model special services [75]. As a planning task develops, the relevant agents will be dynamically grouped into coordination clusters to facilitate their focus on the current task. These clusters will be active as long as required and be destroyed when no longer needed. The agent-based approach makes the whole planning system dynamic, responsive, and distributable.

3.2.3 Function blocks

The concept of function blocks is described in the IEC-61499 specification [76], as an emerging standard for distributed industrial processes and control systems. It is based on an explicit event driven model and provides for data flow and finite state automata based control. There are three types of function blocks: basic, composite and service interface. Figure 5 shows the architecture of basic function block and composite function block. A basic function block defines the fundamental functional relationship of events and data, from which large composite blocks can be built. It uses an appropriate language (such as Structured Text or Java) to define its states and algorithms. Algorithms are encapsulated inside the function block and they can only be accessed by the function block itself. A composite function block consists of several basic function blocks. The definition is given in terms of the data and event connections between function blocks.

Each function block may comprise of an individual, named copy of data structure specified by its function block type, which persists from one invocation to the next. It, especially the basic function block, can have multiple outputs and can maintain internal hidden state information. Each basic function block can also have more than one algorithm [77]. This means that a function block can generate different outputs even if the same inputs are applied. This fact is of vital importance for automatic cutting condition generation, after a function block has been dispatched to a CNC controller, by changing the internal hidden state of the function block or using different algorithms. For example, the same function block designed for pocket-roughing may be shared by two different milling machines with different cutting conditions, by choosing the appropriate algorithm of the function block. Through inheritance, a pocket-milling function block can be reused to specify for pocket-roughing or pocket-finishing, depending on the message received and the algorithm used. For the ease of NC control code distribution, reuse, fault recovery, and dynamic shop floor reconfiguration, process planning data are best encapsulated into function blocks.

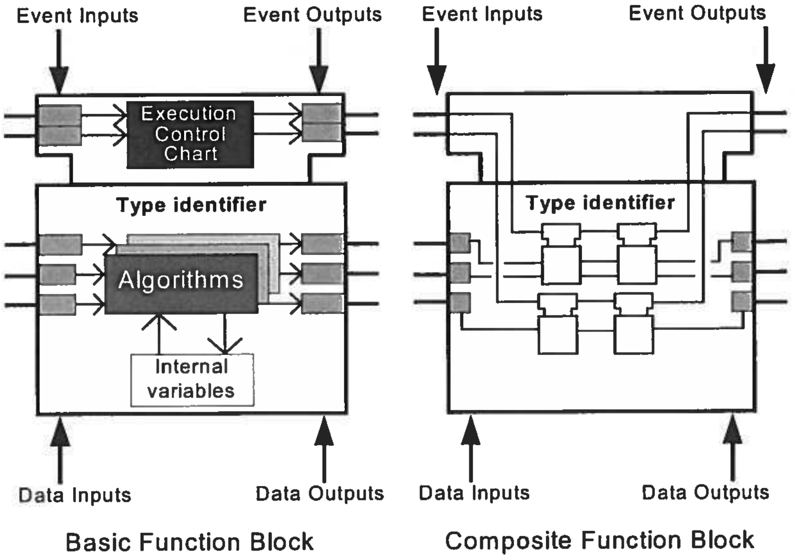

Figure 5. Architecture of basic function block and composite function block

Similar to object-oriented definitions, a function block type can be considered as a class, and a particular function block is an instance of that class. The functionality of multi-inheritance, overriding, and dynamic binding can be used to form a composite function block. However, different from the object-oriented approach, the behavior of a function block is controlled internally by a finite state machine whose operation can be represented by an execution control chart (ECC). As shown in Figure 5, the event flow of a function block determines the scheduling and execution of an embedded machining operation specified by the algorithms (methods) in basic function blocks. In terms of process encapsulation, basic function blocks encapsulate both the data and functions, while composite function blocks only encapsulate basic function blocks. A combination of both basic and composite function blocks is used to define the needed machining operations generated by our DPP system.

3.3 Expected Performance of DPP System

The distributed process planning (DPP) should function as a transparent filter between product design and CNC control. It should be able to transfer and process the design data so as to meet the requirements of subsequent CNC machining. Based on the assessment of existing CAPP systems, available technologies and requirements that form today's industry, the expected performance of DPP system can be summarized as follows.

- Intelligent: to be able to handle uncertainty and to increase probability of success of controlled process.

- Fault Tolerant: to be able to react to the failure and to find substitution for the purpose of quick fault recovery.
- Portable: to apply DPP modules, especially the Operation Planning (OP) module, to different platforms including open CNC controllers.
- Extendable: to be able to include new databases and knowledge, or be adaptable to new applications.
- Distributable: to be able to distribute function block-embedded process plans over a set of CNC machine controllers.
- Reconfigurable: to be adaptive to the dynamic situations including job delay, product changeover, tool and machine breakdown, etc.
- Ease of Use and Reliable: to be easy to install and use. The system functionality should be consistent and reliable.
- Reusable: to be able to reuse most part of the DPP functions and modules.

4 ARCHITECTURE DESIGN FOR SUPERVISORY PLANNING

As mentioned in Section 3.1, the main difference between traditional CAPP systems and our DPP is that the DPP has a two-level structure; it separates the generic data from the machine-specific ones and makes the complex decision-making of process planning distributed [78]. Within the two-level structure, because the supervisory planning is mainly based on the information analysis of design data and manufacturing knowledge, it is possible to keep this part of process plan generic, resource-neutral, and relatively static, whereas the operation planning is affected by the capacity of resources, economic aspects, as well as the real-time status of machining process. It is more resource-driven and dynamic. In this research, supervisory planning is facilitated by machining feature and manufacturing knowledge based reasoning, while operation planning is controller-based local optimization. An agent-based execution control serves as a link between the two. Cooperatively, machining features, function blocks and agents are the three key enabling technologies. The focus of this report is the shop floor-level generic supervisory planning.

4.1 Conceptual Architecture

The conceptual architecture of supervisory planning subsystem within DPP is shown in Figure 6.

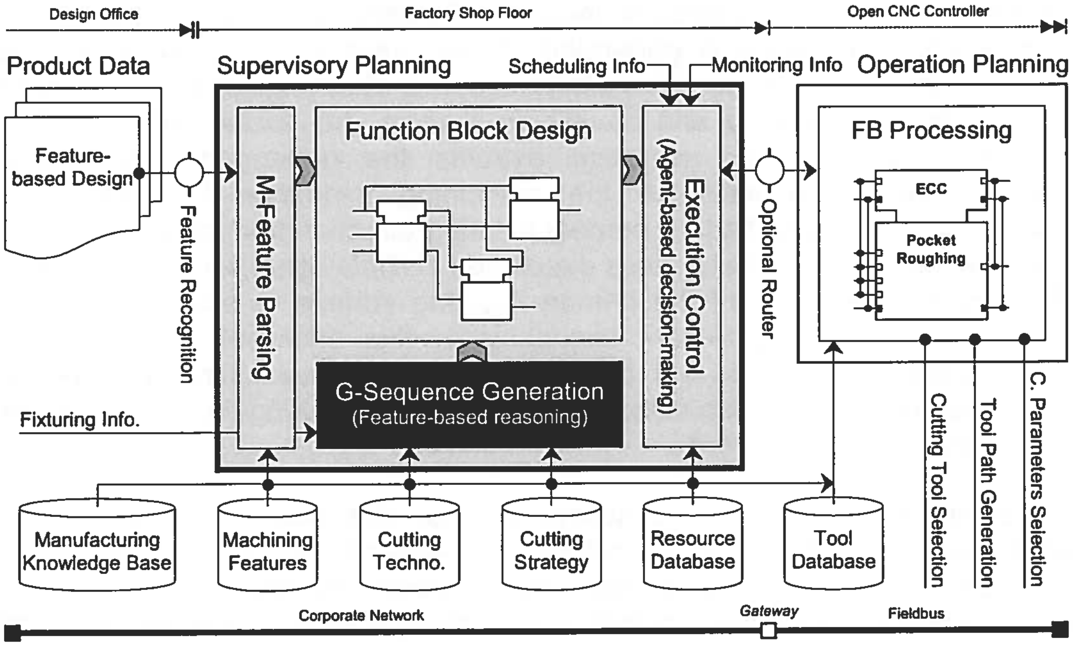

Figure 6. Conceptual architecture of supervisory planning in DPP

The tasks for generic planning are modularized into four parts. They are machining feature parsing, machining feature-based sequence generation, function block design and agent-based execution control. The input of supervisory planning is product data after feature recognition, and the output is partially sequenced machining features with embedded tool type, tool path generation logic and fixturing information, which are grouped into different setups and encapsulated into function blocks. A network of such function blocks will be dispatched to a selected machine in the shop floor for low-level operation planning.

Machining feature (M-Feature) parsing: this process is crucial, especially for those features that are retrieved by using a third-party feature-recognition utility. Because features are application domain dependent, design features are often insufficiently informative for process planning. Especially they may not represent the actual material volumes to be removed. In addition, for the case of subsequent processing, the loosely couple machining information of each machining feature needs to be extracted and expressed explicitly. The task of machining feature parsing is to map design feature models to enriched machining features. During machining feature parsing, information required by the process planning such as datum reference precedence, tool access directions, cutting tool type, tool path generation logic, feature topology, and the raw material related information must be extracted and recognized for each machining feature.

Generic sequence (G-Sequence) generation: generic sequence generation is the core of the supervisory planning. Some implicit information about machining sequence from the design requirements of a product is identified in this module, and geometric relationships of the materials to be removed are retrieved. Guided by general manufacturing rules and constraints including fixturing and cutting tools, resource-neutral machining sequence is generated. Three steps are followed in the generic sequence generation: 1) critical machining sequence checking, 2) setup planning, and 3) multiple setup sequencing and machining feature sequencing within each setup. *Critical machining sequence* checking extracts the dependency precedence of machining features and indicates the machining sequence from manufacturing constraints; *setup planning* finds a primary locating direction first, and then groups the machining features by their tool access directions; *multiple setup sequencing* follows the critical machining sequence of the primary locating surface to establish a sequential order of setups; *machining feature sequencing* within each setup considers critical machining sequence, cutting tool type, quantity of material removal, and applies geometric reasoning based on a virtually removed volume during the machining process — *intermediate machining volume.*

Function block design: a shop-level generic process plan needs to be dispatched to a dedicated machine controller in a mutually understandable language. On the other hand, the reconfigurable shop floor machining requires a flexible control model capable of real-time control, distributed control, event-driven control and intelligent control to handle unexpected exceptions. In this research, function blocks are chosen for generic machining process data encapsulation and CNC control execution. One of the functions of function block design is to automatically generate a function block network based on the partially sequenced machining features. The sequenced machining features from the generic sequence generation are used as the inputs to function block design. Each basic function block corresponds to a specific machining feature or operation. One task of this research is to define the needed basic function blocks. It includes mapping relationship between function blocks and corresponding machining features, and algorithms to perform each operation. Different function blocks are then connected to a network of function blocks, which represents the sequenced operations in multiple setups. The automatically generated results can also be modified by experienced process planners, if necessary.

Execution control: the networked function blocks (generic process plans) will be dispatched to appropriate CNC controllers for low-level operation planning, optimization, and execution. The tasks of optimal machine tool selection, function block dispatching, and process monitoring are conducted by execution control. The execution control uses agent-based decision-making. During execution control, an optimal machine tool is selected through multi-agent negotiation. It integrates necessary scheduling information to optimize the overall shop-level performance. A special *service function block* will be sent to the selected machine together with other function blocks. In the case of exceptions (job delay, or tool/machine breakdown, etc.), the function blocks will be rescheduled or dispatched to another machine for execution. The service function block is responsible for process monitoring.

4.2 System Dataflow

The system dataflow is shown in Figure 7 using IDEF0 diagrams. The input, output, constraints, and supporting conditions of each module are indicated. Some further considerations about relations among four modules of supervisory planning subsystem can be found in Section 6.

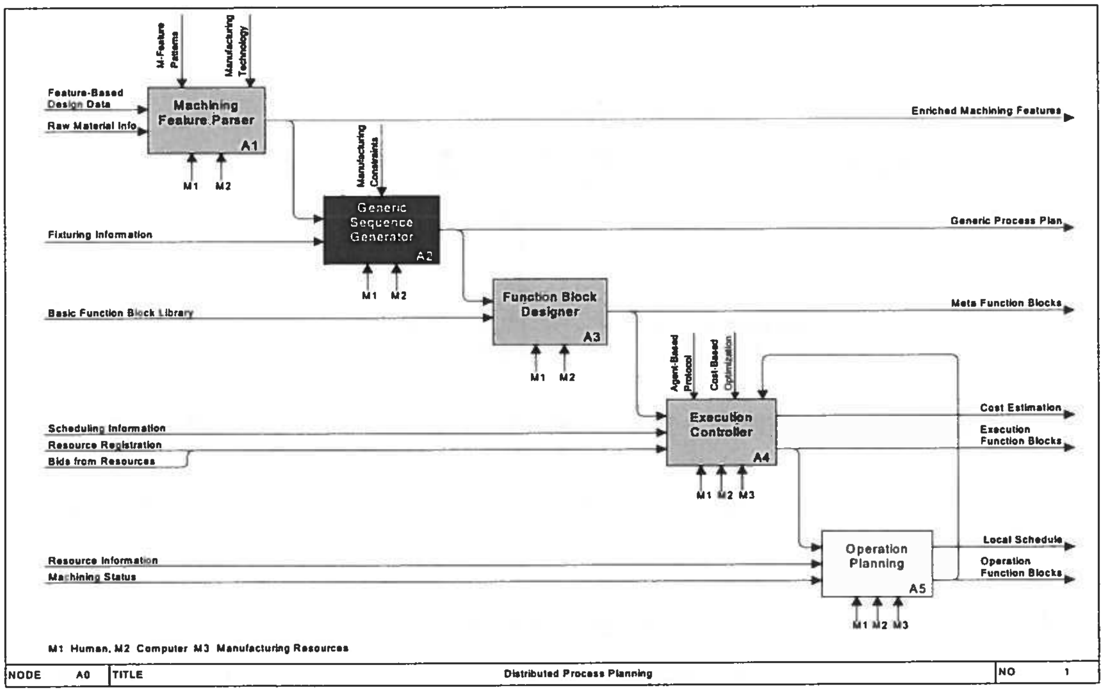

Figure 7. System dataflow of supervisory planning

5 TASK DESCRIPTION OF SUPERVISORY PLANNING

5.1 Machining Feature Parsing

First of all, the link between design data and DPP is feature recognition. Even if the feature-based design has been widely adopted, feature recognition is still necessary. The reason for this is that designers use both additive features such as extrudes and subtractive features such as cuts, and the resulting feature-based models still contain both additive and subtractive features. However, a feature-based model for machining must be composed of only subtractive features since machining is the process that can only remove materials [79]. Also, feature interactions make a design unit unnecessarily a machining unit, which must be decomposed before the real machining process.

Also, the recognized machining features are often insufficiently informative for process planning. More information is required for process planning, such as the information about raw material, feature relationship, and machining strategy. Figure 8 illustrates the function and information flow during machining feature parsing. Feature-based design and raw material information are two inputs to the parsing process. Machining feature patterns and manufacturing knowledge base are the technological support. The main function for this module is creating a new machining feature with its representation scheme. We call this new machining feature model *enriched machining feature*. The outputs after machining feature parsing are enriched machining features.

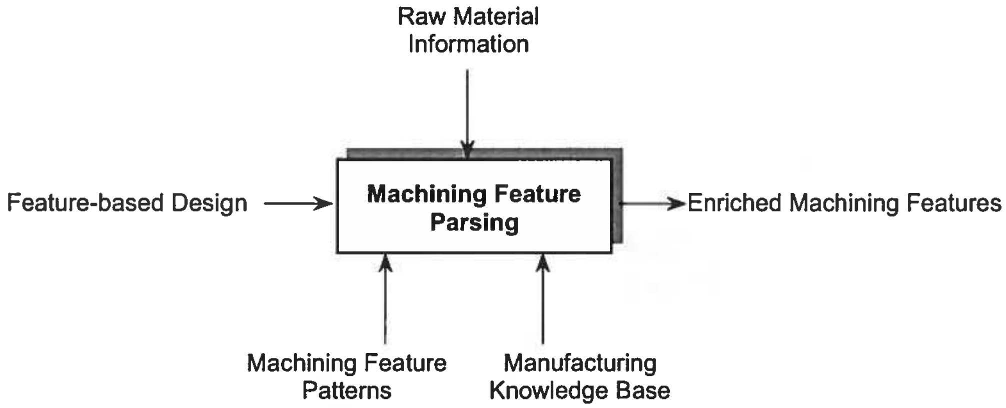

Figure 8. Information flow during machining feature parsing

The function of machining feature parsing module can be divided into several tasks as discussed below.

5.1.1 Maximum machining volume recognition

This task is introduced to represent the raw material information. The maximum machining volume of a feature is achieved by extending its area-contact faces towards the raw material surfaces without destroying the part. The maximum machining volume is then used to intersect itself with the solid model of the finished part. The intersection results in a volume to be removed directly from the raw material to create the feature. Together with intermediate machining volumes, maximum machining volume is crucial in generic machining sequence generation. Methods used for feature recognition can be used for maximum machining volumes, too, such as graph-based method, neural-network-based method, and other hybrid methods [80]. An approach similar to spatial decomposition and composition method is chosen by Sakurai and Chin for extending the area-contact faces, in which only the surfaces of raw material and the surfaces of the area-contact faces are used.

5.1.2 Machining feature classification

Classifying machining features and defining their patterns is the starting point of DPP system. Machining features are different from design features. They should be basic machinable units for machining with loosely coupled manufacturing knowledge. Some typical machining features are given in Figure 2. Further work on precise classification or definition for each machining feature is required.

5.1.3 Manufacturing knowledge base

Manufacturing knowledge basically comes from manufacturing practice. It either has already been explicitly summarized and used as rules, or is still being used only by experienced technicians as personal skills. To perform the process planning task, various manufacturing technology and skills are required from process planners. On the other hand, various process planners' judgments and experiences can lead to the differences in the perception of what constitutes the optimal way of production. Maintaining the consistency of all process plans and keeping them optimized could be a difficult task. One of the important objectives of CAPP is to make the necessary manufacturing knowledge for process planning available as an assistant for every process. Manufacturing knowledge base will contain such kind of information.

Manufacturing knowledge base for machining feature parsing consists of the information about how to fabricate each feature, including its cutting tool type, tool access directions, cutting strategy, and tool path generation logic, etc. Cutting tool type and tool access directions can be used to group machining features into certain setup, while cutting strategy and tool path generation logic are necessary for tool path generation as well as machining time and cost estimation. Generally, manufacturing knowledge base is the foundation for encapsulating machining features into function blocks, choosing a suitable machine for a group of machining features (setup), and generating operation plans at the controller level.

5.1.4 Enriched machining feature generation mechanism

The mechanism of linking the corresponding information, maximum machining volume, and manufacturing knowledge to a certain machining feature should be intelligent and flexible. The enriched machining features of a given part are generated by following certain algorithms and rules. Agent technology can be an enabling tool for this purpose, in addition to general error checking and machine selection. Further research is needed in algorithms/rules definition and agent technology utilization.

5.2 Generic Machining Sequence Generation

Among the four modules of supervisory planning, generic sequence generation is the first module that has been launched. The required input of generic sequence generation is enriched machining features that are ready for process planning. The output is a partially sequenced machining feature list, and will be encapsulated into a function block network for lower-level operation planning. Generic sequence generation is mainly based on the requirements from design specifications and manufacturing constraints. It focuses on setup planning and geometric precedence generation. Two typical test parts designed by using machining features are selected to demonstrate the feasibility of the underlying processing algorithms and rules created for generic sequence generation. Details of the algorithms and rules for machining feature-based sequence generation are explained in a separate IMTI report (IMTI-CTR-XXX (2003/10)). The main function of generic sequence generation is shown in Figure 9.

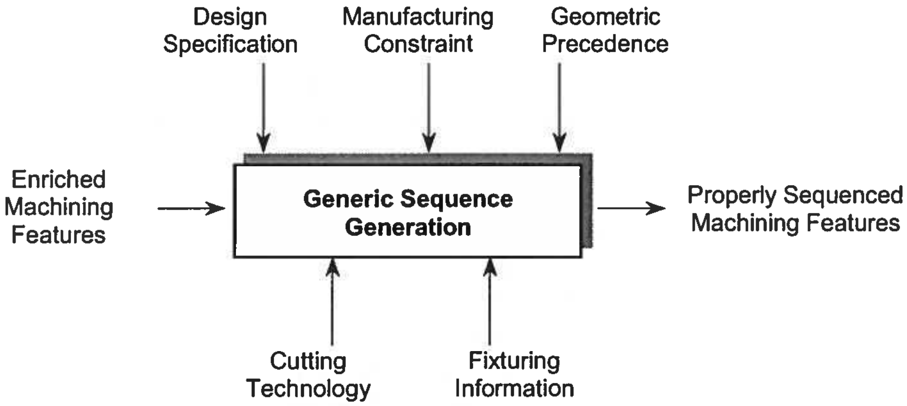

Figure 9. Generic sequence generation

5.2.1 Critical machining sequence checking

Critical machining sequence refers to the sequence that must be followed in the machining processes in order to ensure the design requirements or satisfy specific constraints from manufacturing resources or machining technology. Critical machining sequence will be the base of sequence generation. One of the most important tasks for sequence generation is to guarantee that the tolerance requirements are met when the workpiece is machined following this sequence. To avoid or minimize the machining error stack-up, one of the straightforward rules is to machine all the machining features following their datum dependency precedence if they have a direct datum reference relationship, especially when this relationship is critical, and use the sequence of datum reference features as part of critical sequence to be followed in process planning.

Besides datum reference precedence of machining process, sequence constrained by certain manufacturing operations is another crucial factor that needs to be considered in sequence generation. This usually is not indicated or even considered in the design specification but has significant influence during manufacturing operations to meet tolerance requirements. Such manufacturing constraints need to be checked together with those critical datum reference precedence during the machining sequence generation.

Regarding the manufacturing constraints, they can be a database or knowledge base used to support the process planning, or even the design process in concurrent engineering. This kind of database or knowledge base can be built and improved by combining the knowledge of best practice of engineers and operators.

5.2.2 Setup planning

The basic idea of setup planning is to determine a primary locating direction of a setup, and to group appropriate machining features into the setup according to their tool access directions. The tool access direction(s) of typical machining features used in DPP are embedded as part of machining strategy in each machining feature and illustrated in Figure 2. In a particular setup, features used for fixturing (locating, clamping and supporting) a workpiece can be defined as fixturing features or fixturing surfaces. The primary locating direction is then determined as the surface normal of the primary locating or fixturing surface. At this stage, planar surfaces are considered as candidates of primary locating surfaces, which should be large and accurate enough for locating and supporting a workpiece.

5.2.3 Multiple setup sequencing

As mentioned earlier, a primary locating direction is the surface normal of a primary locating surface that is the major locating datum for determining the spatial position and orientation of a workpiece in one setup. The critical machining sequence must be followed in order to guarantee the tolerance requirements of the part or manufacturing constraints embedded in the required machining operations, in another words, to minimize or avoid the machining error stack-up. Therefore, the multiple setup sequence must be arranged according to the sequence of critical machining sequence.

5.2.4 Multiple setup sequencing

Except the critical machining sequence, the sequence of other machining features cannot be determined by either the datum relationship or the manufacturing constraints. It is largely related to the feature geometry, real cutting conditions and manufacturing resources. It is some sort of optimization with certain objectives, such as characteristics of operation of machining process, economic aspects of manufacturing resources, etc. As mentioned before, resource-related optimization is mainly addressed at the operation planning level of the DPP, whereas the generic sequence of machining features at supervisory planning level is determined based on the information of machining features themselves. The sequence of machining features within each setup must satisfy critical machining sequence first, and is then sorted by using the information of feature geometry and some best practice knowledge.

5.3 Function Block Generation

The generated machining sequence plan will be used for function block design, where enriched machining features are mapped into appropriate basic function blocks. The output of this process is networked meta function blocks. Basic function block library creation, function block generation, and generic process plan development are the main tasks during function block design, as shown in Figure 10.

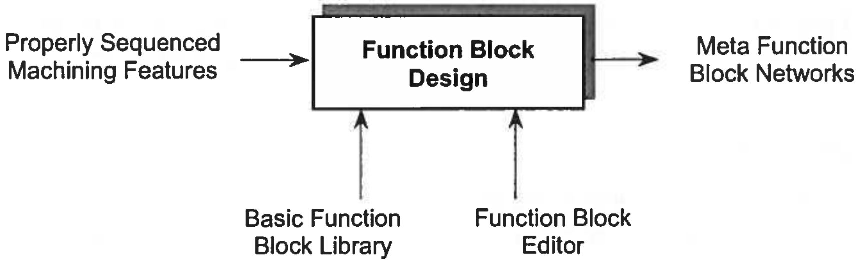

Figure 10. Function block design

5.3.1 Basic function block library

Corresponding to each typical machining feature, a basic function block will be predefined using an appropriate data format (such as Structured Text or XML) to define its states and algorithms. Algorithms are encapsulated inside the function block and they can only be accessed by the function block itself. The basic function block will encapsulate the information of machining features, such as suggested tool type, and tool path generation pattern. It will also define the fundamental functional relationships of event and data of machining process. The basic function block may have multiple algorithms inside for roughing, semi-finishing and finishing. All these basic function blocks will form the basic function block library. Experienced users can modify and create their own basic function blocks, and update the basic function block library under system authorization.

5.3.2 Function block editor

One of the main functions in function block design is to generate a function block network based on the sequenced machining features. This function can be applied at three levels: basic function block, composite function block, and application of a mechanical part, which will represent the processes of a single machining feature, a group of machining features in one setup and a mechanical part, respectively. The units in the function block library can form composite function blocks. A composite function block consists of several basic function blocks and/or other composite function blocks. The definition is given in terms of the data and event connections between function blocks. An application of a mechanical part will be a function block network built by certain basic and composite function blocks. It is done through a function block editor.

Function blocks not only encapsulate the information, reasoning rules/algorithms about corresponding machining features and their fabrication processes, but also represent the complex sequence relationships and event handling mechanisms to facilitate the execution, monitoring and control of the enriched machining features. In DPP, there are three types of function blocks generated at different stage for machining feature encapsulation, execution control and machining operation realization.

Meta function blocks (MFBs) that encapsulate the machining sequence plan (sequence of setups and machining features) are the output during function block design. As its name suggested, a meta function block only contains the information of machining process of a given feature. It is a high-level process plan template, with suggested cutting tool types and tool path generation patterns, for subsequent manufacturing tasks. Every time the same product enters the system or the system needs to re-dispatch function blocks (execution function blocks), the system will use the meta function blocks to create instances for new task applications.

Execution function blocks (EFBs) are function blocks ready to be downloaded to a specific machine. Basically, EFBs are created by instantiating MFBs and by combining with particular manufacturing resource information, such as machine tools, lot size, and fixtures. Generic process plan will be specified, and represented as a set of EFBs. At this stage, setup will be the unit for task dispatching and estimation-based optimization, so that the monitoring functions can be fulfilled for each specified setup. With resource specific information added, the EFBs are no longer portable between multiple machine tools. Appropriate EFBs are generated by the *Execution Control* module of the DPP for a selected machine.

The structure of an operation function block (OFB) is similar to that of an EFB. However, OFB specifies and applies EFB in a real time machining environment with more detailed, machine-specific information (tool ID, cutting conditions, tool path, and machining status for each machining feature). Operations in each setup at any time instant, and the values of variables in EFBs will be updated or even overridden. Moreover, the controller-based optimization will be performed in real time. We use two different terms of EFB and OFB to distinguish a given function block, because they are two separate entities with different level of details in content, fulfilling different levels of execution, residing in different system modules, and may be deployed in physically distributed computers or controllers.

5.4 Execution Control

As shown in Figure 6, Execution Control is the bridge of supervisory planning and operation planning, which makes itself an important integration point of data, activities and decision-makings in the entire DPP system. Unlike traditional CAPP systems, scheduling information and monitoring events are integrated and handled at early stage of process planning by the Execution Control module. Both machining feature based estimation and real time shop floor status are considered at this stage, and multi-agent technology will be adopted as a decision making engine. The functionalities of execution control include agent-based resource selection, setup merging (for 4-axis/5-axis machines), estimation-based optimization, dynamic scheduling and monitoring, as shown in Figure 11.

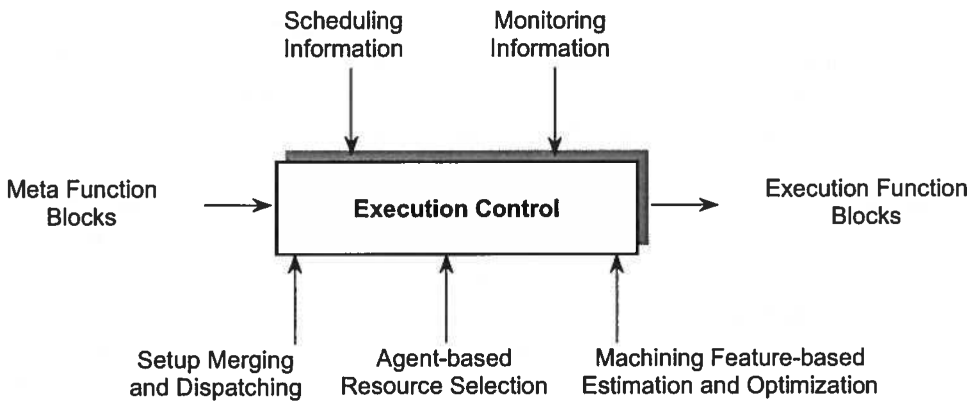

Figure 11. The tasks of execution control

5.4.1 *Agent-based resource selection*

Agent-based resource selection is crucial for supervisory planning and operation planning integration. All the top-down information from generic planning or scheduling system and bottom-up information (real time resource status and machining processes) are sent here for event handling and decision-making. A multi-agent system will be adopted for distributed resource and information negotiation and coordination, as shown in Figure 12.

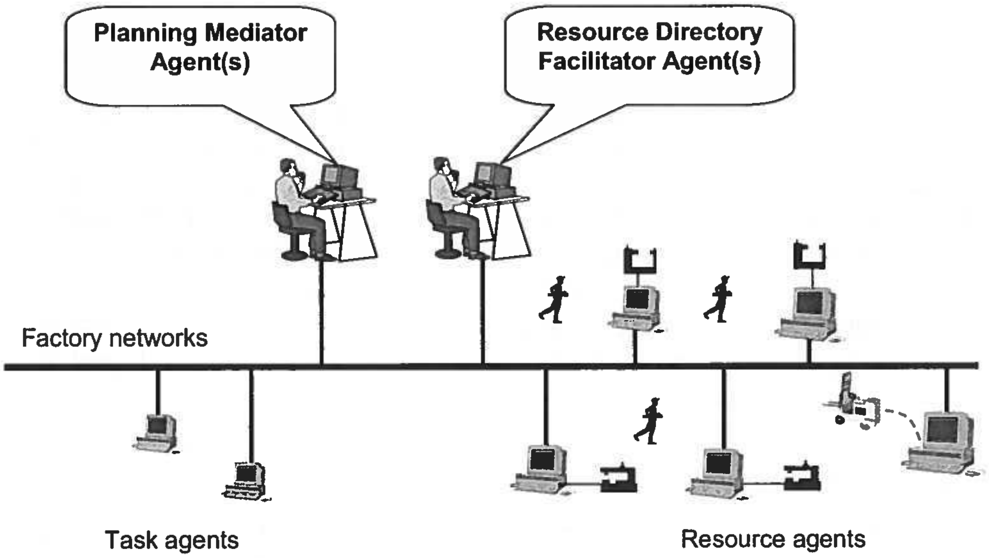

Figure 12. Multi-agents for distributed manufacturing system integration

In the illustrated multi-agent system, manufacturing resources in the shop floor (such as workers, cells, machines, tools, fixtures) as well as tasks (such as parts, setups, features, operations) are represented as agents. Special services (such as planning mediator for facilitating machining task planning, and resource directory facilitator for providing registration and administration services) will be modeled. Other agents, such as database agent and information agent for providing information management, may also be necessary. Contract Net Protocol [81][82] is considered for agent coordination based on cost or time estimation. The key for choosing agent technology as a decision-making engine for resource selection and task dispatching is that agent technology provides a natural way to overcome some critical problems that traditional approaches are facing, such as limited expandability and reconfiguration capabilities for unexpected situations and shut down by a single point of failure, etc. Agent-based approach can help DPP realize dynamism and fault tolerance in dynamic shop floor environment.

5.4.2 Set-up merging and dispatching

After the multi-agent system has given the result of task allocation, the 3-axis-based resource-independent generic process plan can be further adjusted to fit specific machines. For example, in the case of a 5-axis CNC machine tool, two tasks (setups) of the same product assigned to this machine may have the chance of being machined by one single setup. Furthermore, the tool information can also be considered at this stage to do sequence optimization because a machine is already specified at this stage. The purpose of setup merging and sequence optimization is to make sure that the function blocks downloaded to a machine are relatively optimal. We call the function blocks after the setup merging process the "execution function block" to indicate that the generated function blocks now are ready to be dispatched to machines.

5.4.3 Machining feature-based cost estimation and optimization

The criterion for manufacturing resource selection is the machining cost of each setup (after setup merging), under the condition of satisfying quality requirements. Machining cost calculation is mainly based on machining time and material cost [83]. The estimation of machining cost can involve two extremes regarding the data requirements [84]. The most accurate method requires specification of materials, tools, work holding and details of the operations used to manufacture the component, whereas the simplest method requires the shape and size of the initial stock material, the quantity of material to be removed and the cost of material removal per unit volume [85].

In our DPP, the most accurate methods cannot be used in optimization of the manufacturing resource selection, because the range of data required is beyond what is available at the execution control stage. A method that attempts a compromise between the accurate methods that use too many detailed factors and the simple methods that provide rough-cut accuracy can be investigated based on the information of machining features themselves and generic plan generated by supervisory planning. After generic sequence generation and function block design, each setup is consists of certain partially sequenced machining features and their GD&T specifications, as well as suggested tools type and tool path patterns. Machining cost is proportional to machining time, which includes operation time and non-operation time. Cutting condition can be estimated using the tables of recommended cutting conditions for various tool types, tool diameter and component material combinations. The tool path length can be estimated based on suggested tool path pattern and feature dimensions. Then, the operation time (machining time) can be calculated. Chip-to-chip tool change time and other non-operation time can be retrieved from past experience and approximated for modification into mathematical optimization objective functions [83][85].

5.4.4 *Early integration with scheduling*

Traditionally, process planning and shop floor scheduling have been two rather separate activities within the manufacturing organization. Process planning determines how a product should be manufactured by focusing on the pure geometric and technological requirements of tasks. It assigns machines, cutting tools and cutting parameters to each process based on some ideal but unrealistic assumptions such as unlimited resources and an idle shop floor. Without the consideration of real-time machine workload and shop floor dynamics, the process plans made off-line during the planning stage are often out of touch on the shop floor at the time of task execution. On the other hand, the scheduling using rigid process plans has already lost the optimal options. Owing to the recognition of these shortcomings, there is a need for the integration of manufacturing process planning and scheduling systems for generating more realistic and practical plans to be used in the shop floor.

In the Execution Control module, the real time scheduling information about the shop floor will be integrated at the resource selection stage as one of the optimization factors. With the multi-agent approach, global scheduling of a shop floor will be optimized based on the real time local schedule of each machine. At the same time, each local schedule will be updated as long as a job has been assigned to this machine by the global schedule. This makes the scheduling dynamic and resource selection for process plan more realistic and practical.

5.4.5 *Function block monitoring*

Function blocks provide a new solution for shop floor monitoring and control. A function block monitoring module is actually a graphical interface to users, from which all the status and events happening during machining processes can be displayed graphically on the screen. Most incoming events from real time machining process will cause this module to change the graphical updates of function blocks. By introducing the concept of function block, monitoring and control can thus be done at each machining process unit rather than the task level (complete G code of a task) in most production management systems.

6 Conclusions

The objective of our DPP is to generate process plans that are dynamic, responsive, flexible, and fault tolerant in the changing shop floor environment. The system architecture of the DPP is designed based on a two-layer structure, consisting of supervisory planning at shop floor level and operation planning at controller level. It can separate generic process planning information from machine-specific one, and enables a distributed decision-making for the whole process planning that corresponds to the distributed manufacturing resources and information.

The main focus of this report is architecture design and task description of each module of supervisory planning. The tasks of supervisory planning is manufacturing resource-independent, and based mainly on the machining feature information and manufacturing rules. Especially, enriched machining features are generated by adding raw material information and by extracting feature relationship and loosely coupled machining information. Machining features are used as information carriers at different stages of the DPP system. Enabled by the DPP and manufacturing resource-independent reasoning approach, the high-level process plans become generic and open, with increased flexibility and dynamism.

Furthermore, function blocks and agents are other two enabling technologies used in DPP. A generic process plan can be encapsulated into a function block network. As robust, reusable and executable units, function blocks used in DPP not only represent the complex sequence relationships, but also embody event handling mechanisms to facilitate the execution, monitoring and control of the machining feature fabrication. Agent technology, on the other hand, is becoming an important approach for developing distributed intelligent manufacturing systems. The reason is that agent technology provides a natural way to overcome fragility and to increase responsiveness in centralized hierarchical manufacturing planning system. It shifts the focus of automation from being hardware centric to software centric, providing further flexibility.

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APPENDIX: SUMMARY OF LATEST CAPP SYSTEMS

Name of system	Research group	Key features	Application domain
FBD-MANS	Lee et al., 1999 USA [28]	Encapsulating the protrusions with virtual convex polytope to generate the manufacturing feature model.	Feature recognition
GCAPP	Gu et al., 1997 Singapore [29]	Using a fuzzy model and feature manufacturability to evaluate feature priorities and identify important features.	
OOSA for CAPP	Chep et al., 1999 France & Italy [30]	Representing manufacturing feature by using the object-oriented system analysis method.	
N/A	Ming et al., 1998 China [31]	Developing an information model for CAPP by using the object-oriented modeling and the Product Data Exchange Step/Standard of Exchange Product data (PDES/STEP) technologies.	
ATS	Edalew et al., 2001 UK [51]	Developing a procedure for tool selection and determining cutting parameters and cost utilizing mathematical modules and heuristic data.	Tool selection
EXCATS	Arezoo et al., 2000 UK [53]	Selecting cutting tools and conditions for machining operations by using an expert system.	
VITOOL	Maropoulos et al., 2000 UK [54][55]	Presenting the methods for feature creation, operations and tools selection, and machining time estimation.	
IPAC	Yellowley et al., 1999 Canada	Integrating process planning and remote monitoring within an existing open architecture CNC.	
M-TSP	Kim & Suh, 1998 Korea [62]	Determining the optimal group and sequence of operations for a multistage by incorporating the expert system and mathematical programming.	Sequence planning
N/A	Balasubramanian & Raman, 1998 USA [59]	Modeling gradual process variables in path planning including forces, temperatures, and tool wear.	Path planning

N/A	Wu & Zhang, 1998 China [64]	Employing object-oriented technology to represent setup planning knowledge and generate alternative set-ups and fuzzy-set theory to produce optimal set-ups.	Set-up planning
N/A	Ong & Nee, 1996 Singapore [63]	Presenting a Fuzzy-set based approach for concurrent constraint set-up planning.	
IPP in OKP	Tu et al., 2000 New Zealand & China [66]	Proposed CAPP framework includes the reference architecture for structuring a CAPP system in virtual OKP, a new CAPP method named incremental process planning (IPP), and an optimal cost analysis model.	System integration
CoCAPP	Zhao et al., 2000 China [45]	Presenting a new cooperative agent model for process planning that satisfies five major requirements: autonomy, flexibility, interoperability, modularity and scalability.	
N/A	Gu et al., 1997 Canada [48]	Describing a bidding-based approach to the integration of computer-aided design, process planning, and real-time scheduling.	
N/A	Ming et al., 1999 China [38]	Developing the architecture of a hybrid intelligent inference model using both expert system and neural networks for implementing a CAPP system.	
AAPP	Zhang et al., 1999 USA & China [20]	Proposing object-oriented manufacturing resource modeling (OOMRM) and adaptive agent-based process planning (AAPP).	
CFACA	Liu, 2000 China [67]	Developing a framework by using component technology in feature-based design and process planning.	
N/A	Srinivasan & Sheng, 1999 USA [68][69]	Dividing process planning into two phases - microplanning and macroplanning. In microplanning, process, parameters, tooling and cutting fluids are selected for the individual features. While in macroplanning, interactions between features are examined.	
CAPPES	Kryssanov et al., 1998, Japan [39]	Introducing a new formal method to design CAPP expert systems.	
CyberCut	Smith & Wright, 1996 USA [40]	Providing following services via Internet: (1) a design for manufacturing CAD interface, (2) a choice between two CAPP systems, and (3) access to an open architecture machine tool for fabrication parts.	

MAPP for CyberCut	Dornfeld et al., 1999 USA [49]	Describing a multi-agent process planning module in a networked machining service environment.	
IAI-CAPP	Chang & Chang, 2000 Taiwan [70]	Integrating fuzzy logic (FL) and artificial neural networks (ANN) to perform the dynamic recognition and adaptive-learning tasks of plans, adopting the ideas of important (critical) feature concept for evaluating the suitability of existing process plans for incoming product designs, and utilizing the technique of expert system.	
ANN-based CAPP	Devireddy & Ghosh, 1999 Canada [23]	Integrating the featured-based design and artificial neural net works-based planning aspects of manufacturing.	
N/A	Zhang et al., 1997 Singapore [21]	Adopting genetic algorithm to deal with process planning problems in a concurrent manner in generating the entire solution space by considering the multiple decision-making activities.	
3I-PP	Khoshnevis et al., 1999 USA [71]	Describing the architecture of a new integrated process planning system with three modules: feature completion, process selection, and process sequencing. A knowledge-based approach is applied to feature completion and process selection, and a space search algorithm to sequencing.	
N/A	Morad & Zalzala, 1999 Malaysia & UK [22]	Providing an approach to integrate process planning and scheduling using genetic algorithms. The criteria include machine capabilities, cost to operate, and processing times.	Planning scheduling integration
N/A	Little et al., 2000 UK [72]	Proposing and developing planning and scheduling reference models for engineer-to-order sector. Extended event process chains and planning-scheduling process models are created.	

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DPP: Distributed Process Planning

An Approach to Generate Flexible and Adaptive Process Plans for Reconfigurable Manufacturing Shop Floors

In the last decade, the change in market requirements towards a larger variety of products in smaller batch size has led to the concept of next generation reconfigurable manufacturing systems (RMS), being an integrated network of distributed resources simultaneously capable of combined knowledge processing and material processing. Within an RMS, the manufacturing processes are complicated, especially at machining shop floors. In addition to those fluctuating job shop operations, unpredictable issues, such as job delay, urgent job insertion, fixture shortage, missing tools, and even machine breakdown etc., are regularly challenging manufacturing companies.

Traditional process planning methods are time-consuming and error-prone if applied to this dynamic environment. The dynamic RMS environment like this requires creating an intelligent and distributed process planning system that is responsive and adaptive to the unpredictable changes of distributed production capacity and functionality. In response to the requirement, we propose a new methodology of *distributed process planning* (DPP) to improve the flexibility and dynamism of process plans that are tolerant to the fluctuations in reconfigurable shop floors.

A process plan generally consists of two parts: *generic* data (machining method, sequence, and machine information) and *machine-specific* data (tool data, cutting conditions, and tool paths). Therefore, a two-layer structure with shop-level *supervisory planning* and machine-level *operation planning* is designed to deal with the respective data processing. The former focuses on product data analysis, machining feature parsing, setup planning, machining process sequencing, and machine selection; whereas the latter considers jig/fixture selection and the detailed working steps for each machining operations, including cutting tool selection, cutting parameter assignment, tool path planning, and control code generation. Three enabling technologies are adopted in our DPP to facilitate process planning:

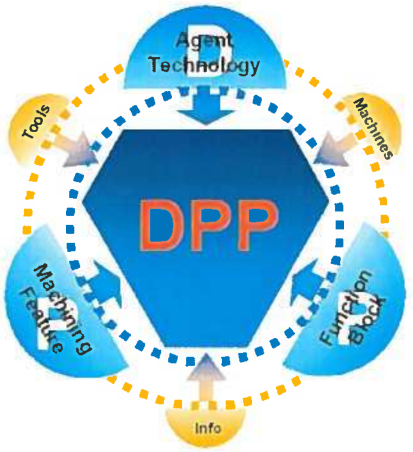
- *Machining features* are used as information carriers from product design to CNC machining
- *Agent technology* is applied to enhance distributed decision-making among different modules and resources
- *Function blocks* are selected for event-driven execution control and run-time process monitoring

At the supervisory planning level, well-sequenced machining features together with their associated machining data are encapsulated in appropriate function blocks. They are then dispatched to appropriate CNC controllers for low-level operation planning, optimization, and execution. At the operation planning level, the function blocks are finalized by assigning actual tool data and cutting conditions. As a controller is knowledgeable of the machine being controlled, it assures that each function block is also locally optimized.

Enabled by the DPP, a so-generated shop-level process plan becomes generic and open, with increased flexibility and dynamism against changes in fluctuating job shop operations. Because of its open architecture, the DPP shows promise of dynamic integration with resource scheduling.

For further detailed information, please contact:

Lihui (Ian) Wang, Ph.D., P.Eng.
Research Officer, NRC-IMTI
800 Collip Circle, London, ON N6G 4X8, Canada
Phone: (519) 430-7084 Fax: (519) 430-7090
Email: lihui.wang@nrc.gc.ca



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