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ORIGINAL ARTICLE

Integrated manufacturing process planning and control based on intelligent agents and multi-dimension features

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Abstract Dynamic manufacturing environments require a flexible process planning and control system in response to changing manufacturing resource availability, production uncertainty, and dynamic machining conditions. To address these issues, this paper proposes a novel integrated process planning and control method based on intelligent software agents and multi-dimension manufacturing features. An integration framework with three modules including generic process planning, shop floor process planning, and online process control is developed. An intelligent agent-based approach is adopted for achieving intelligence and autonomy of individual software modules and components. An ontology-based multi-dimension manufacturing feature model is proposed to facilitate the communication and collaboration between process planning and control, as well as to speed up the decision-making of intelligent agents. The feasibility and flexibility of the proposed method are validated through a proof-of-concept implementation.

Keywords Manufacturing automation · Process planning · Process control · Intelligent agents · Manufacturing features · Integration

1 Introduction

Manufacturing enterprises today are facing increasing global competition. They have to change their way of production management to improve their global competiveness. At the shop floor level, changes of manufacturing resource availability induced by machine tool failures or emergent orders always enforce the process planning department to conduct process replanning in order to adapt to these changes, which is very time consuming and costly [1]. At the machining level, various machining problems may emerge during the machining process due to complex machining conditions. The changing machining conditions such as spindle thermal deformation, tool failure, chatter, and workpiece deformation induced by clamping force, cutting force, and material inner stress [2] have significant impacts on machining quality and efficiency. The computer numerical control (CNC) controller or the PC platform of CNC controller lacks of intelligence and autonomy to respond to these situations. The integration of machining process planning and control is always required to improve the subsequent machining process [3], and the process control information can be used as knowledge for process planning. However, such integration is difficult due to the separation of these modules. Manufacturing data management should be encapsulated by schema and manipulation rules in a data model [4]. The manufacturing knowledge representation and digital representation of manufacturing information, especially the multi-dimension representation of manufacturing information, are becoming more important for facilitating the cooperation of machining processes and manufacturing systems.

The challenges involved in the integration of process planning and control can be summarized in the following aspects:

– Multi-dimension information model. The information model encompasses multiple perspectives of different machining stages and scales, from process planning, online machining, to machining feedback. An unambiguous and unified definition of the concept involved in the information model is required.

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– Interoperation and cooperation among different modules. The integration system should have the ability to respond to changing machining conditions at both the shop floor level and the machine tool level, to interoperate and manage data from different application views, and to realize the cooperation of different modules.

To address these challenges, a flexible and integrated process planning and control system is proposed, where an online process control module with intelligent and autonomous characteristics is integrated with process planning modules, as well as the feedback from online control to process planning is established. Intelligent agents are adopted to represent function modules for decision-making to realize the intelligence and autonomy of individual software modules and components. An ontology-based multi-dimension manufacturing feature model is established to facilitate the integration of process planning and control and to speed up the decision-making for intelligent agents.

The rest of the paper is organized as follows. Section 2 reviews some related literature. 3 presents the proposed framework and the multi-agent system. Section 4 describes the proposed multi-dimension feature model. Section 5 shows some proof-of-concept implementation results. Section 6 concludes the paper and discusses our future work.

2 Literature review

Integration of process planning and process control has been an active research field for many years. The literature review below is focused on process planning and control information models and process planning and control integration methods.

2.1 Process planning and control information models

Various information models based on features and existing standards have been proposed and developed in the literature to facilitate process control. Features which are defined as geometric shapes with certain engineering semantics are used to bridge the computer-aided process planning (CAPP), computer-aided manufacturing (CAM), and CNC. Campos and Hardwick [5] proposed a solution to link traceability requirements to feature data by taking the advantage of features as the kernel technology for computer-aided design (CAD) and CAM integration. Feature-based Standard for the Exchange of Product Model Data (STEP) is proved to be an effective method for the integration of CAD, CAM, and computer-aided inspection (CAI) [6]. Dynamic feature modeling method considering real machining conditions for process planning and optimization has been considered to be a promising approach [7]. STEP-numerical control (NC)-based information modeling is widely researched in recent years. A STEP-NC data model for turning operations was developed by POSTECH of Korea and ISW of Germany [8]. A universal manufacturing platform that utilizes the STEP-NC standard data models and mobile agents was developed by Newman and Nassehi [9]. Wang et al. [10] proposed an adaptive CNC system by integrating STEP-NC and Function Block international standards to enhance the machining process control. STEP-NC information model has rich information of geometry and process and supports bidirectional data flow from CAM to CNC. However, it is still suffering from the representation of intermediate state of feature and monitoring data, and the feature represented by STEP-NC information model is only the final state. Other standards such as MTConnect and Instrumentation, Systems, and Automation Society (ISA) are also adopted for process control. Campos and Miguez [11] presented a traceability scenario where standards such as MTConnect and ISA-95 supports are adopted, which can relate data records with the corresponding machining operations in a STEP-NC part program. MTConnect and ISA are good at project management, but they lack of representation of geometric information.

2.2 Integration methods for process planning and control

Process planning deals with the selection of necessary manufacturing processes and determination of their sequences, as well as the selection of manufacturing resources to "transform" a design model into a physical component economically and competitively [12]. The aim of process control is to take actions to the changing manufacturing environments and machining conditions to guarantee manufacturing quality and efficiency, where monitoring and inspection approaches are always involved [13, 14]. The integration of process planning and control can maximize the capability of manufacturing resources and manufacturing efficiency [15], which has been extensively investigated in the past couple of decades. The related integration methods can be roughly classified into distributed loose-coupling approaches and information model-based centralized approaches.

2.2.1 Distributed loose-coupling approaches

Intelligent agents are mostly adopted for distributed loose-coupling integration systems [16, 17]. Shen et al. [18] proposed a concept called iShopFloor—an intelligent shop floor based on the Internet, web, and agent technologies, which focuses on the implementation of distributed intelligence at the manufacturing shop floor level to respond quickly to changing shop floor environments and customer demands. Zhao et al. [19] presented a cooperative agent model for process planning satisfying five major requirements: autonomy, flexibility, interoperability, modularity, and scalability. Allen et al. [20] developed a multi-agent framework, where agents represent individual features of a component and work independently and cooperatively to generate process plans for discrete component manufacturing. Wang and Lin [21] studied the application of radio frequency identification (RFID) techniques and multi-agent system (MAS) in developing an agent-based agile manufacturing planning and control system to respond to the dynamically changing manufacturing activities and exceptions. Agent-based approach is also used for the integration of process planning and scheduling, so as to optimize process planning by taking into account limited manufacturing resources allocated over time among parallel and sequential activities [22, 23].

Function Block is also adopted for process planning and control integration in recent years [24]. Wang et al. [25] proposed a Function Block-enabled process planning approach to handle dynamic changes during process plan generation and execution, where Function Blocks are adopted to sense environmental changes on a shop floor so as to make the generated process plan adapt itself to the dynamic shop floor environment. Mařík and Lažanský [26] proposed a solution for real-time control, where the concept of holonic agent is introduced and the standard of Function Block is adopted.

Hierarchical methods are widely adopted for ensuring performance of various functions at different levels, which are proved to be adaptive to distributed changing manufacturing environments. Wang and Shen [27] proposed a distributed process planning (DPP) methodology to address changing shop floor environments, with two-level decision-making: supervisory process planning and operation planning. Because the operation planning is performed at the machine level, simulation is not easy to be executed. Wang et al. [28] proposed a decision-making approach toward adaptive setup planning that considers both the availability and capability of machines in a shop floor, where a two-step decision-making strategy is utilized for generating machine-neutral and machine-specific setup plans at each stage.

Feedback is widely used to close the process planning and control loop in distributed loose coupling approach. Lee et al. [29] demonstrated an enhanced closed-loop CAM architecture using a Petri-net-based analysis mechanism, which incorporates shop floor uncertainties to generate process plans and alternative processing sequences under dynamic conditions such as machine failures. Yilmaz [30] presented a feedback control optimization framework for a sensor development and fabrication process, where an intelligent model was configured in a closed-loop feedback control framework to optimally automate the sensor manufacturing process. Katz et al. [31] presented a closed-loop machining cell for turbine blade finishing which integrates a robotic surface finishing device with an electro-optical and noncontact precision measuring system. Li et al. [32] proposed a feedback method from inspection to process planning based on feature mapping for aircraft structural parts so as to improve machining process quality. Barari [33] presented a CAM-based inspection methodology which can be used to model and understand the real machining errors. This method can be utilized for process control or closed-loop machining. Loose coupling methods are very flexible, but the smoothness of the communication among individual modules should be enhanced.

2.2.2 Centralized approaches

Information models are widely used for the centralized integration of process planning and control by taking advantages of sharing information of different manufacturing stages or views. Suh et al. [34] presented a kind of architecture for the shop floor programming system including STEP physical file interpretation, feature recognition, process planning, part program generation, and verification, where STEP-NC is adopted as information model. Rauch et al. [35] proposed an advanced STEP-NC controller for intelligent machining processes, where online or real-time adaptive parameters optimization can be realized. Zhao et al. [36] proposed a framework of STEP-NC-enabled closed-loop machining, where machining and inspection processes are closed in the machining process. Brecher et al. [37] introduced the integration of measuring technology into a STEP-NC-based process chain in order to save the results of the manufacturing process in a set of data and feed them back to the planning process. Information model-based methods are relatively tight coupling methods, which are not very flexible.

The research efforts mentioned above have made important contributions to the literature on the integration of process planning and control. However, we believe that there is still a strong need to develop (1) an integration of process planning and control with flexible and smooth characteristics by taking advantages of both loose coupling methods and centralized methods, (2) a process planning and control integration architecture which can adapt to complex machining conditions and changing resource availability, and (3) an information model with multi-dimension information which can facilitate both quick and intelligent process planning and control. This paper presents our recent work in this direction.

3 Agent-based process planning and control framework

This work is an extension and continuation of our previous work on intelligent agent-based iShopFloor [18], where the integration of process planning and scheduling is addressed. This paper focuses on the integration of process planning and control aiming at changing manufacturing environments and machining conditions. The work is extended to online stage, and a flexible and smooth integration system is expected. A distributed process planning and control framework including generic process planning, shop floor process planning, and online process control is proposed in this paper, as shown in Fig. 1.

The functionality of each module is defined by considering information availability of each stage and the computational load of the CNC system so as to maximize the flexibility and efficiency of the manufacturing system. In the proposed framework, the feedback from shop floor process planning to generic process planning and the feedback from online module to generic process planning and shop floor process planning are established. Intelligent software agents are utilized to realize the intelligence and autonomy of individual modules, and a multi-dimension manufacturing feature model is developed to provide multiple perspectives to view process information at different stages.

3.1 Process planning and control framework

3.1.1 Generic process planning module

Generic process planning module is in charge of the following tasks: selection of clamping and positioning methods, selection of machine tool types, macro-machining-sequence decision-making, and machining operation decision-making. Basically, the clamping and positioning methods are decided by the structure and the accuracy requirement of the parts, so they can be decided according to the information of the parts at the preliminary stage. At the generic process planning stage, the type of machine tool only refers to the horizontal type or vertical type, because they are closely related to the fixture and positioning methods, as well as the definition of the axis directions of machining operations. Further selection of the machine tool type will be completed during the detailed process planning. Macro-machining-sequence decision-making refers to the sequence planning of setup positions of the whole machining process of the workpiece. Each machining operation is subject to one certain setup position. Machining operations refer to the machining method of each machining feature, such as face milling or flank milling. Machining features are defined as geometric shapes with certain machining semantics. Therefore, machining features are defined with respect to machining methods.

Generic process planning is executed based on feature techniques. For the selection of clamping and positioning methods, a case-based reasoning approach is adopted based on typical templates according to process planning rules. Typical templates are collected and indexed by features, i.e., each fixture and positioning method is feature related. The impacting factors of clamping and positioning are expressed by the form of features, and therefore when features are input

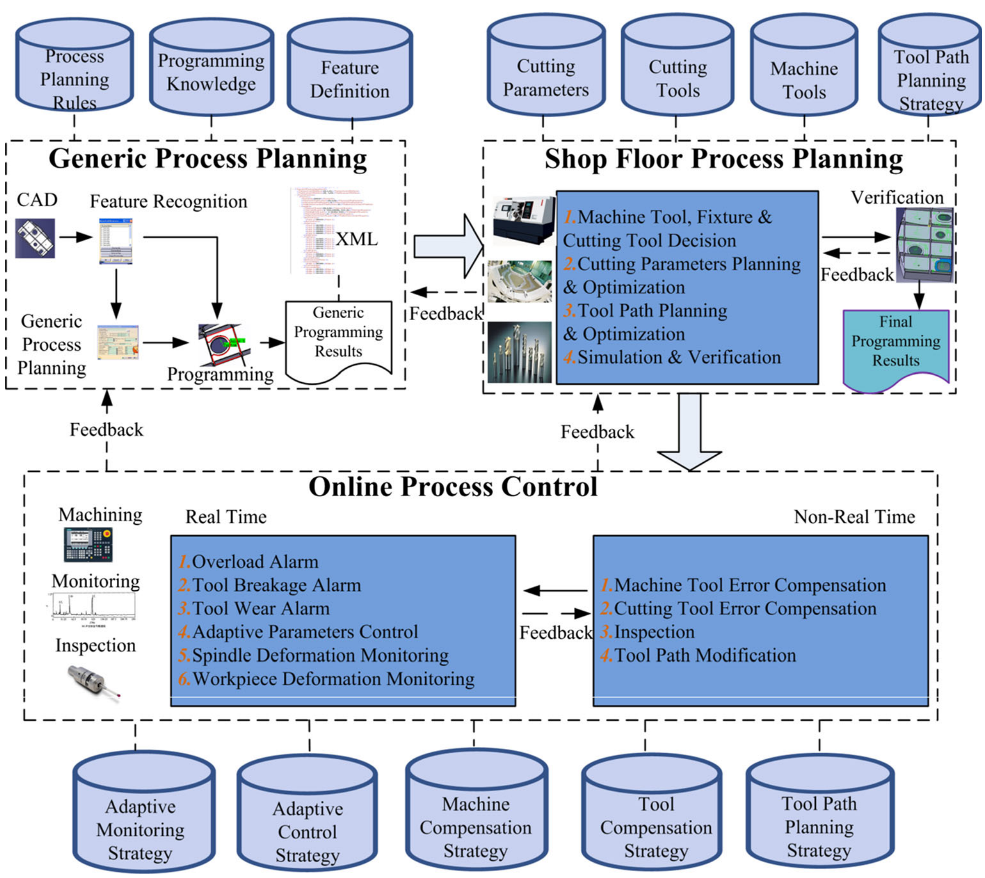


Fig. 1 Architecture of process planning and control system

into the clamping and positioning module, the similar templates are selected and can also be modified to fit exactly to the objective part. Take the aircraft part as an example, the clamping method decision should consider the distribution of pocket features, the thickness of the bottoms of pocket features, the surface type of the bottoms of pocket features, and the height distribution of rib features. When the feature and its information are obtained, the clamping and positioning template of similar parts is selected.

Machining operations are decided according to feature definition. A holistic attribute adjacency graph-based feature recognition method is adopted to extract machining information from 3D CAD models. This feature recognition method was previously developed by our research team [38]. The machining features should be predefined. CAD model and machining orientation are inputs of the algorithm. The extracted machining information includes geometric information and property information of machining features, as well as some general information of the part such as its height. The geometric elements of the machining feature are mapped to the corresponding machining operation as driving geometry according to programming knowledge, which can be used to generate tool paths with addition of machining parameters. The property information of machining features includes the height of the feature, the maximum permitted diameter of cutting tool, the corner radius of the feature, and some other useful information for further process planning. Basically, generic process planning is executed automatically, and some manual interaction is involved by process planners to improve the planning results.

The generic process planning results are relatively independent without tying up with specific machine tools or cutting tools. Under this context, the generic process planning results have a lot of flexibility. On the other hand, the generic process planning results contain sufficient information for further detailed process planning. As shown in Fig. 2, the generic process planning results are saved as eXtensible Markup Language (XML) files based on features by taking the advantage of its well-structured characteristics. Features of 3 axis machining and 5 axis machining can both be represented using XML files. The generic process planning results are exported after the machining operation of features is decided. The information in XML files is comprised of three parts: general feature information, driving geometries, and feature properties. This information is used by the other modules for further process planning.

3.1.2 Shop floor process planning module

Comparing to generic process planning, more detailed process planning is done by the shop floor process planning module due to the determination of more concrete manufacturing resource information. Such detailed process planning includes the specification of machine tools and cutting tools, the sequencing of machining operations, and the selection and optimization of cutting parameters. Besides, tool path planning, optimization, and verification are also included in this module. At this stage, the availability of machine tools and cutting tools is obtained, so machine tools and cutting tools can be decided through further process planning. By using machine tool information and cutting tool information in addition to part information and feature information derived from generic process planning, cutting parameters are selected by using optimization algorithms. Tool paths are generated by using the above information. As machine tool is specified, the dynamic characteristics of machine tools and CNC systems such as acceleration/deceleration performance can be obtained, so tool paths and cutting parameters can be further optimized, i.e., the strategies and speed at some features such as corners can be optimized for safer and more efficient machining. In terms of cutting speed in corners, the curvature of the corner and the acceleration of CNC system should be considered. Besides, since the materials to be removed at the corner are usually more than other areas, the machining speed should also be optimized for the consideration of cutting force. Tool path verification is very important for ensuring the quality and safety of machining, especially for complex parts by high-speed machining, which is almost impossible to complete the programming once without any defects, and the consequences made by faults are always very severe. In this module, geometric errors and conflicts are checked by tool path verification, and the problems will be fed back to process planners for revision. In case the process planning results from the generic process planning are not suitable for shop floor process planning, the problems are fed back to the generic process planning module for adjustments.

Considering the complex machining conditions in machining processes, process monitoring using sensors is always required. So where to monitor and by what kind of sensors are planned automatically based on features in this module. Inspections of key machining features are also planned in this module.

After the shop floor process planning is completed, the process planning results are represented in an XML file based on features, and the tool paths results are output into NC code files based on features after post processing.

3.1.3 Online process control module

Machine tool compensation, cutting tool compensation, monitoring, inspection, and adjustment are handled in the online process control module. In contrast to traditional methods, this online process control module is autonomous and automated. Some of the compensation values of the machine tool can be determined before machining, while others are calculated according to machining conditions. For example, the

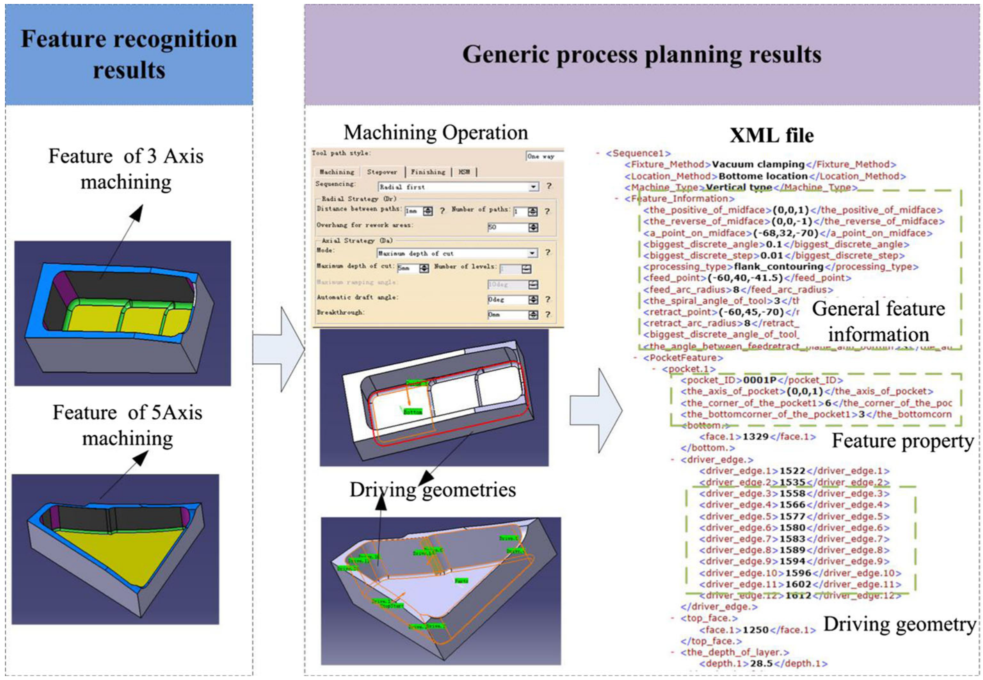


Fig. 2 Generic process planning results

compensation of the thermal deformation of a spindle should be completed by monitoring the temperature of the spindle during machining. The cutting tool compensation includes static compensation and dynamic compensation, i.e., the wear of the tool is measured before machining, and the tool is compensated according to the wear degree. During machining, the tool is compensated dynamically by monitoring the tool wear. Vibrations signals, force signals, and power signals are used to monitor the machining state. Furthermore, a multi-sensor fusion method can make the monitoring results more robust. The monitoring strategies are decided by the shop floor process planning results. Spindle condition, cutting tool condition, and workpiece condition are monitored. Some key interim geometry machining conditions and final machining results are inspected online. Some tool path or cutting parameter modifications may be needed according to the monitoring or inspection results, and those functions are completed by the online process control module. The monitoring and inspection data are fed back to the generic process planning module and the shop floor process planning module. These data are also stored in a knowledge base for optimizing future parts. This is very useful for the production of small batches or for the first part of a large batch, whose machining processes are not always mature.

3.2 Construction of the system based on intelligent software agents

In order to implement the proposed process planning and control framework, the autonomy and intelligence of individual modules and the cooperation between the modules should be addressed. Intelligent software agents are utilized to cope with these requirements in this paper.

3.2.1 Types and functionalities of intelligent software agents

Agents have the properties of dynamic, agile, scalable, and fault tolerant, which can meet the requirements of desired manufacturing systems [22]. A multi-agent system can achieve the goal of collective, possibly heterogeneous, computational entities, having their own problem-solving capabilities and being able to interact among them in order to reach an overall goal [39]. An agent-based approach is particularly suitable for distributed process planning [40]. By taking the advantages of agent technologies, a multi-agent system is constructed:

- A feature recognition agent, a preliminary manufacturing resource planning agent, and a machining operation planning agent are created for the generic process planning module.
- A detailed manufacturing resource decision agent, a cutting parameters selection agent, a tool path planning agent, and a simulation and verification agent are created for the shop floor process planning module.
- A monitoring agent, an inspection agent, and a machining adjustment agent are created for the online process control module.
- A number of resource management agents, a multi-dimension feature management agent, and a facilitator agent are developed to facilitate the cooperation among the agents mentioned above.

The functionalities of these agents are described below:

- Feature recognition agent: to extract geometric and attributive information of parts. This agent works at a CAD/CAM environment, where CAD models are required for feature recognition. The features are predefined by engineers and system developers, and then the features are extracted from CAD models. The feature recognition results are output into XML files.
- Preliminary manufacturing resource planning agent: to select fixture and positioning methods, positioning sequences, and machine tool types. This agent is realized based on features. The features for resource selection are input of this agent. Manufacturing resource templates of typical parts are connected with this agent for manufacturing resource selection using case-based reasoning.
- Machining operation planning agent: to complete machining operation selection and driving geometric programming. This agent is realized based on features. Feature recognition results are used for machining operation planning, i.e., to decide what kind of machining operation and what kind of parameters for machining operation. Process planning rules are connected to this agent.
- Detailed manufacturing resource decision agent: to complete the selection of machine tools and cutting tools. This agent is performed as more detailed manufacturing information is determined. The working mechanism is similar to that of preliminary manufacturing resource module, but for more detailed information.
- Cutting parameter selection agent: to complete the selection of optimization of cutting parameters for machining operations. Cutting parameters are selected based on features by considering the specified machine tools. This agent is connected with cutting parameter library, and the selected cutting parameters are also optimized by optimization algorithm for particular features.
- Tool path planning agent: to finish tool path generation and optimization. The complete tool path is generated by this agent according to the determined manufacturing information. The generated tool path is identified by features, so the whole manufacturing cycle can be controlled for the tool path and can be easily modified. The tool path optimization is also made by considering the specified machine tools, so the characteristic library of machine tools is connected with this agent. NC codes are generated by this agent.
- Simulation and verification agent: to do tool path simulation and verification in order to check whether interferences exist. This agent can realize the identification of machining simulation errors based on features and send the errors back to tool path planning agent for modification. The communication between the two agents can make the tool path modification more convenient.
- Monitoring agent: to collect and analyze sensor signals. It includes both hardware (monitoring sensors) and software (for monitoring results analysis). The interfaces to connect hardware tools and software tools are implemented in this agent, so the real-time information can be collected and processed.
- Inspection agent: to collect and analyze inspection data. Similar to the monitoring agent, it includes both hardware (inspection devices) and software (for inspection data analysis).

Spindle compensation, cutting tool compensation, tool path adjustment, and cutting parameter adjustment are executed by the machining adjustment agent. Other agents are described in the following subsection.

A federated architecture is adopted to organize these agents since the federated multi-agent architecture can coordinate multi-agent activities through mediation to reduce overheads, ensure stability, and provide scalability, which is suitable for large-scale engineering applications [22, 41].

3.2.2 Cooperation among agents

The cooperation among agents is realized through resource management agents, the multi-dimension feature management agent, and the facilitator agent.

The resource management agents are used to manage manufacturing resources including fixtures, machine tools, and cutting tools, as well as the cutting parameter databases. The fixture management agent, the machine tool agent, the cutting tool agent, and the cutting parameter agent are included in resource management agents. The resource management agent looks up the available resources in the resource databases according to the requirement.

The multi-dimension feature management agent is designed especially for multi-dimension feature information management. The feature recognition results, all process planning results, and tool path results are all stored in the multi-dimension feature management agent. The monitoring results and inspection results are also stored and managed by the multi-dimension feature management agent. A multi-dimension feature instance is created when feature recognition results are input, and it will be destroyed after the workpiece machining is finished, and all the multi-dimension feature-related information is archived in the database for subsequent uses. The information stored in multi-dimension feature management agent can be retrieved by other agents.

The facilitator agent is designed to facilitate the communication, collaboration, and coordination among all the agents. Most communications among agents are through the facilitator agent. However, some agents (mostly those agents with result outputs) are communicating with the multi-dimension feature management agent directly in order to reduce the communication overhead.

Figure 3 shows the relationship among agents, where FA represents the facilitator agent, RMA represents the resource management agents, and MFMA represents the multi-dimension feature management agent. We can find that the facilitator agent plays an important role for the communications among agents and the resource management agent and the multi-dimension feature agent are key agents, which facilitate the system performance.

4 Multi-dimension feature modeling

4.1 Definition and representation of multi-dimension feature

Traditional features are represented as three-dimension geometry in addition to some property information, and the geometry information is the final state of features. It is not adequate to cope with complex and distributed manufacturing environments. In this paper, a multi-dimension feature model is proposed. One more dimension, i.e., the time dimension is added to three-dimension geometry as the fourth dimension to construct the multi-dimension feature, which will facilitate the integration of process planning and control. Additional dimensions will be added to the feature model and will be reported in future publications.

The final state which expresses the desired geometry shape and some property information is used to represent three-dimension geometry. The required tolerances and some other process information for features are attached to three-dimension geometry as features' properties.

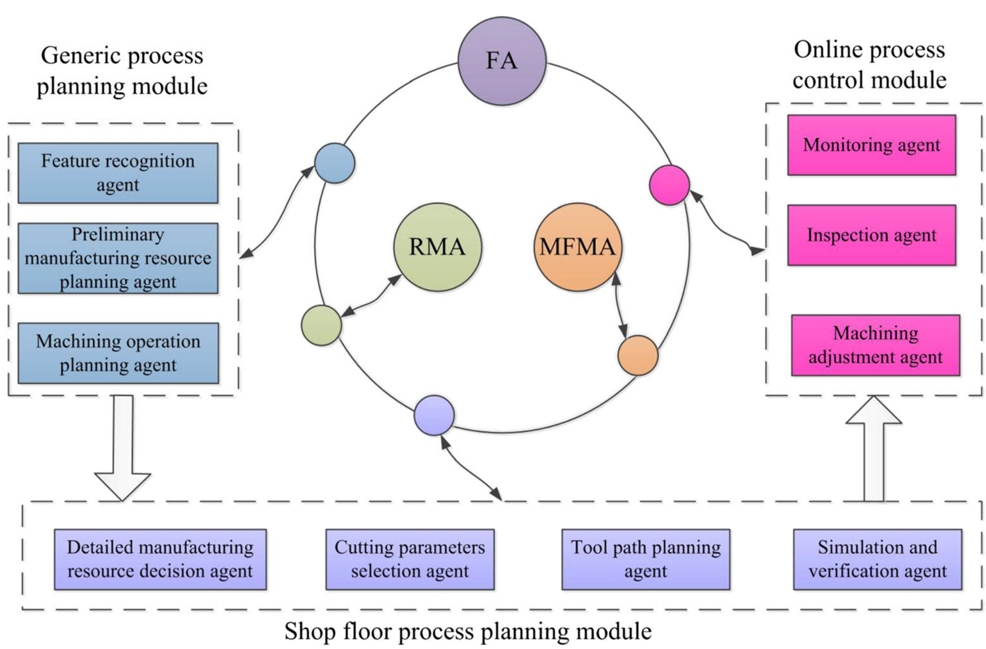
The time dimension is represented by the machining operations, machining strategies and cutting parameters, the interim states of features, the physical machining conditions, and the inspection results. The machining operations transform raw materials into designed part shapes by machining sequences. The interim states of features are the consequence of the corresponding machining operations. The physical machining conditions are reflected by monitoring signals during machining operations. The inspection results are obtained by measuring and analyzing geometric and dimensional errors between some key machining operations. The properties xwhich are used to represent the time dimension are continuously changing over time. Another important characteristic of these properties is that they are complementary to three-dimension geometry. The proposed multi-dimension feature model is shown in Fig. 4.

So, the multi-dimension feature can be represented as follows:

$$MDF = (G\_X \perp G\_Y \perp G\_Z) \cup T \quad (1)$$

where *MDF* represents multi-dimension feature, *G_X* represents x-axis dimension, *G_Y* represents y-axis dimension, *G_Z* represents z-axis dimension, and *T* represents time dimension.

Fig. 3 Relationship of multiple agents



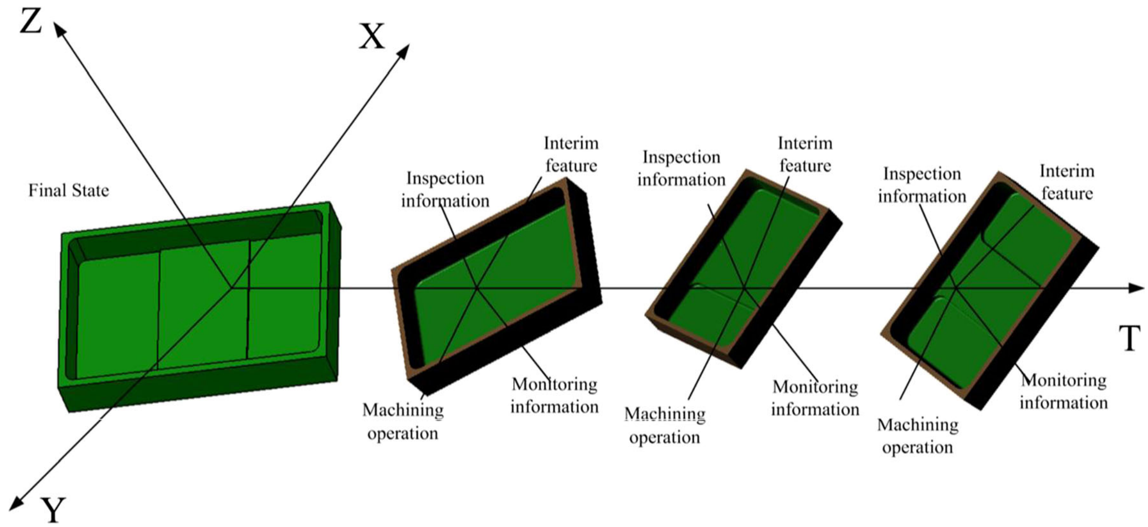


Fig. 4 Multi-dimension feature model

The three-dimension geometry is contained by geometry information and property information including geometry properties and process property.

$$TDG = G\_I \cup G\_P \cup P\_P \quad (2)$$

where *TDG* represents three-dimension geometry, *G_I* represents geometric information, *G_P* represents geometric property, for example, the corner radius, and *P_P* represents process property, for example, the accuracy requirement of the geometry.

The time dimension can be represented as follows:

$$T = MO \cup M\_S\_P \cup ISF \cup PS \cup IR \quad (3)$$

where *MO* represents machining operation, *M_S_P* represents machining strategies and cutting parameters, *ISF* represents interim state of feature, and *IR* represents inspection results.

Because the in-process and related information is well organized by the time dimension, the integrated process planning and control are becoming feasible.

4.2 Ontology-based multi-dimension feature modeling

In order to facilitate the communication and collaboration among multiple agents, ontology is adopted to represent the multi-dimension feature. Ontologies are used to describe and represent the domain knowledge. Ontology represents a shared understanding of domain knowledge and consists of concepts used to describe the domain knowledge and the relationships between those concepts. When ontologies are used in multi-agent systems, there are two advantages: (1) Ontologies enable agents to work cooperatively to communicate with each other; (2) ontologies make the available information more accessible to automated agents [42].

Ontologies include classes, instances, concepts, properties, and relationships. In this paper, the multi-dimension feature is defined using ontology. Different kinds of multi-dimension features are defined as different kinds of instances, and each feature is deemed as an instance when being used. The related concepts are defined without ambiguity for the communication among agents. The hierarchy and relationships of the ontology definition are shown in Fig. 5, which are defined using UML.

In Fig. 5, the classes of multiple-dimension feature (Multi_D_F), three-dimension geometry (Three_D_Geo), time dimension (Time_D), geometric information (Geometric_Inf), geometric property (Geometric_Pr), process property (Process_Pr), machining operation (Machining_Op), interim feature (Interim_F), monitoring information (Monitoring_Inf), inspection information (Inspection_Inf), machining strategy (Machining_St), and cutting parameter (Cutting_Para) are defined. Semantics are used to define the concepts to make the definition unambiguous. For example, geometric information is defined by the geometric elements, and each element is defined with a name, for example, side wall, top face, corner, and bottom, which are unified in the system. The required machining operation can be decided according to the semantic descriptions for corresponding features.

The concept and definition of interim feature, monitoring information, and inspection information are described in details in this section. Interim feature is generated by intermediate machining operation, which is described by shape and dimension. For example, the interim feature of a bottom machining is described by the shape of bottom surface and the thickness of the interim state, and the shapes are always represented by mathematical functions. Monitoring

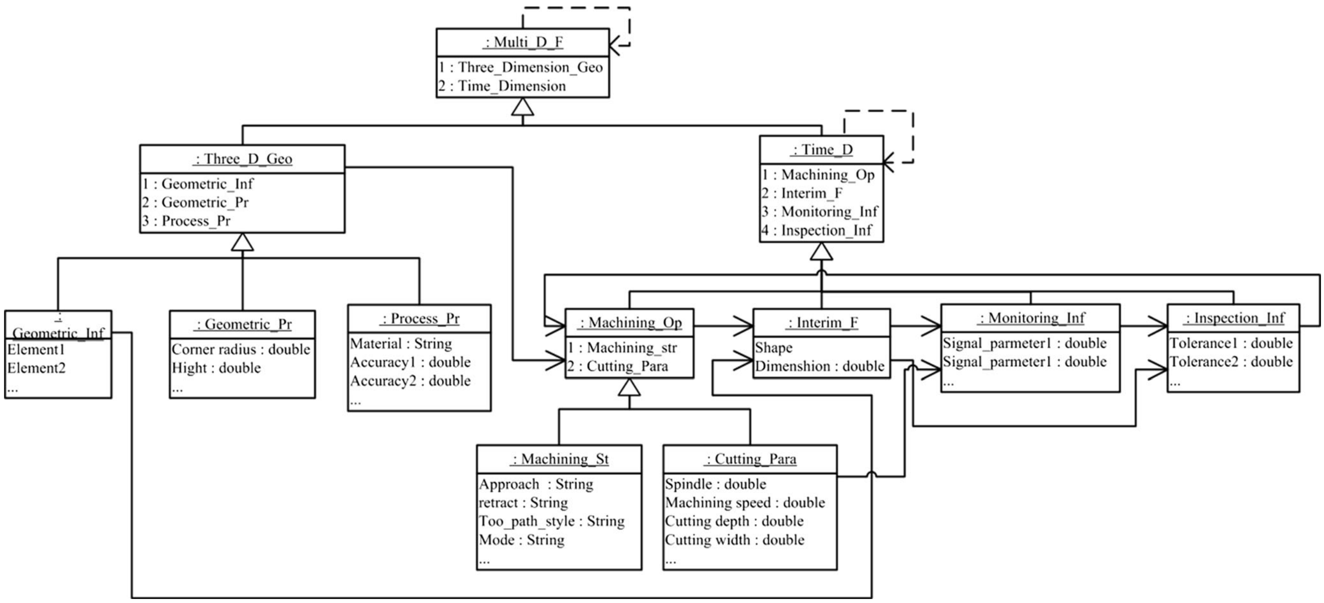


Fig. 5 Hierarchy and relationship of the ontology definition

information is described by monitoring signals which are collected by monitoring devices during machining. The signal characteristics are extracted by signal processing. Inspection information is described by inspection results such as flatness, roughness, thickness, and circularity.

The relationships among the classes are also defined in Fig. 5. The class Multi_D_F and the class Time_D are both unitary relationship. Three_D_Geo has a binary relationship with machining operation, because machining operations of features are decided according to the semantics of the class Three_D_Geo. Machining operation may be adjusted in the subsequent part machining according to the feedback of inspection results. The class Interim_F has a complex relationship with Machining_Op and Geometric_Inf, because interim feature is the results of machining operation, which depends upon geometric information. The class Monitoring_Inf is a reflex of physical machining condition of current interim feature and cutting parameters, so the safety thresholds of monitoring characteristics are decided according to interim feature parameters and cutting parameters. Sometimes, cutting tool information is also taken into account. The rules for recognizing machining conditions are built based on the relationships. Interim state inspection is triggered by monitoring signal analysis, and predefined triggering messages (including keywords) are sent for inspection. The inspection is executed according to the kind of interim feature. All the relationships mentioned above are basis for reasoning rules, which can speed up decision-making.

Instances are defined for actual execution. There are different kinds of features for a particular kind of part. Taking aircraft structural parts for example, there are pockets, ribs, holes, and profiles. Each kind of feature has its own definition, and it is expressed by semantics, as features are defined as geometric shapes with certain engineering semantics. There are different kinds of machining operations with different machining strategies and cutting parameters. Take face milling as an example, back and forth, and spiral strategies are frequently adopted as machining strategies in the machining of aircraft structural parts. Different monitoring devices or inspection types all have different kinds of instances. The properties of all of the instances are defined respectively.

4.3 Implementation of multi-dimension feature model in the proposed multi-agent system

The main functions of the multi-dimension feature model in the multi-agent system are the representation and transfer of machining information and the representation of knowledge and rules which support the decision-making by agents. Due to the advantage of ontology-based multi-dimension feature model, the agents in charge of different manufacturing stages can share the same concept of classes, instances, and properties, which can avoid misunderstanding with each other.

The representation and transfer of machining information by multi-dimension feature are the basis of the integration of different agents, especially for the agents of different manufacturing stages. The multi-dimension feature model provides different scales and perspectives for different manufacturing stages. For example, in three-dimension geometry view, it shows the information of final state and the manufacturing requirement of the part; in time dimension view, it shows the whole manufacturing process information in time series even much more additional information to know about the process. In fact, it can show different perspectives such as design information, process planning information, monitoring information, and inspection information. Multi-dimension feature makes the manufacturing process management much more convenient.

The representation of knowledge and rules based on multi-dimension feature is also the basis for the decision-making of multiple agents. The manufacturing knowledge includes manufacturing resources for parts, machining operations for features, cutting parameters for machining operations, the monitoring signal thresholds for machining conditions, inspection methods for features, and inspection results criterion for features. Such knowledge is represented based on multi-dimension feature and provides references for decision-making of agents, i.e., each kind of knowledge is linked with a kind of feature and feature's properties. The rules are created based on knowledge, the relationships described in multi-dimension feature modeling. The rules include the selection of manufacturing resources, the selection of cutting parameters, the selection of machining operations, the recognition of machining conditions based on monitoring signals, and the evaluation of inspection results. The knowledge and rules are saved in databases, which can be used by multiple agents.

5 Proof-of-concept implementation

The modules of generic process planning and shop floor process planning are implemented on a CAM platform, and the related agents are developed and integrated on the CAM platform. In this paper, CATIA™ is adopted as the CAM platform. The feature recognition agent (FRA), the preliminary manufacturing resource planning agent (PMRPA), the machining operation planning agent (MOPA), the detailed manufacturing resource decision agent (DMRDA), the cutting parameters selection agent (CPSA), the tool path planning agent (TPPA), and the simulation and verification agent (SVA) are developed based on the CAM platform.

The online process control module is implemented on an open CNC system platform, and the related agents are developed and integrated with the CNC system. The monitoring agent (MA), the inspection agent (IA), and the machining adjustment agent (MAA) are developed based on the CNC platform.

The multi-dimension feature management agent (MDFMA) and the FA are developed on dedicated computers. RMA are developed and associated with the resource database, where machine tool management agents are implemented. Each machine tool is deemed as an agent, and its availability can be obtained directly by communicating with the agent.

The communication among the agents is realized through a local network, and the communication is using XML. The structure of XML files is defined according to the modeling of multi-dimension feature. The content in XML files can be understood without ambiguity by all the agents. The implementation framework is shown in Fig. 6.

The details of a pocket manufacturing by using the proposed approach are described for illustration. The pocket feature is defined by bottoms, sidewalls, tops, and corners, and the connection relationships are also defined. For example, a corner is connected with two sidewalls in the horizontal direction. The geometric properties include the corner radius, the height of the pocket, and the maximum tool diameter that the pocket can be permitted to machine. The machining operations for machining pockets are sequenced by roughing,

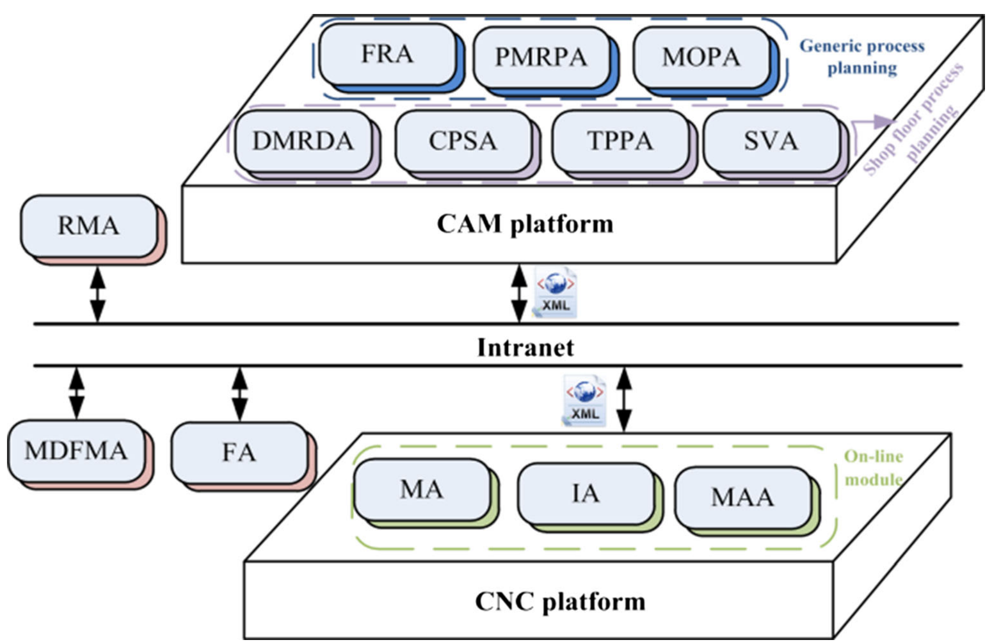


Fig. 6 Implementation framework

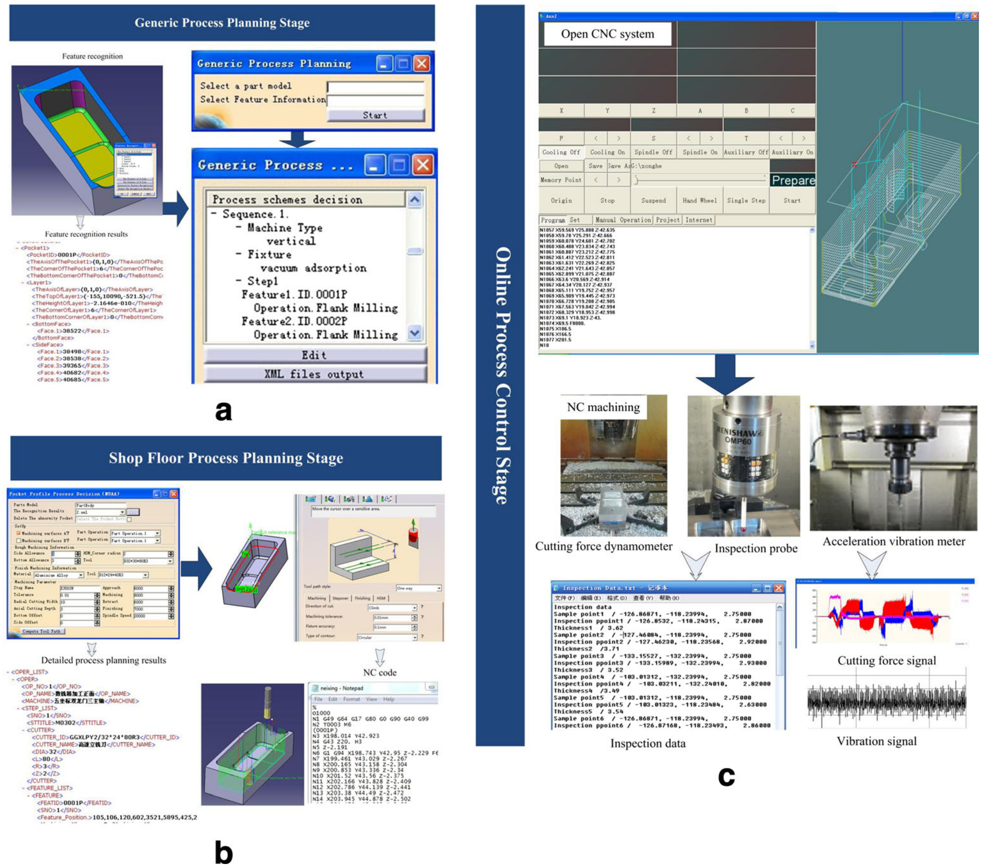


Fig. 7 Implementation flow and interfaces. **a** Generic process planning stage. **b** Shop floor process planning stage. **c** Online process control stage

bottom face milling, flank milling, and corner milling. Cutting force dynamometer is adopted for the monitoring during pocket machining. The peak, the mean, and the power spectrum of monitoring signals are extracted as signal characteristics. The interim state of the bottom machining is inspected due to its ease of deformation. The multi-dimension feature model is built based on the definition described above.

The implementation scenario is shown in Fig. 7, where the flowchart and interfaces are illustrated. As shown in Fig. 7a, the three-dimension geometry information is extracted by the feature recognition agent, and the information is output into an XML file. The preliminary process planning is done by the generic process planning agent based on feature recognition results. Based on the feature recognition results and

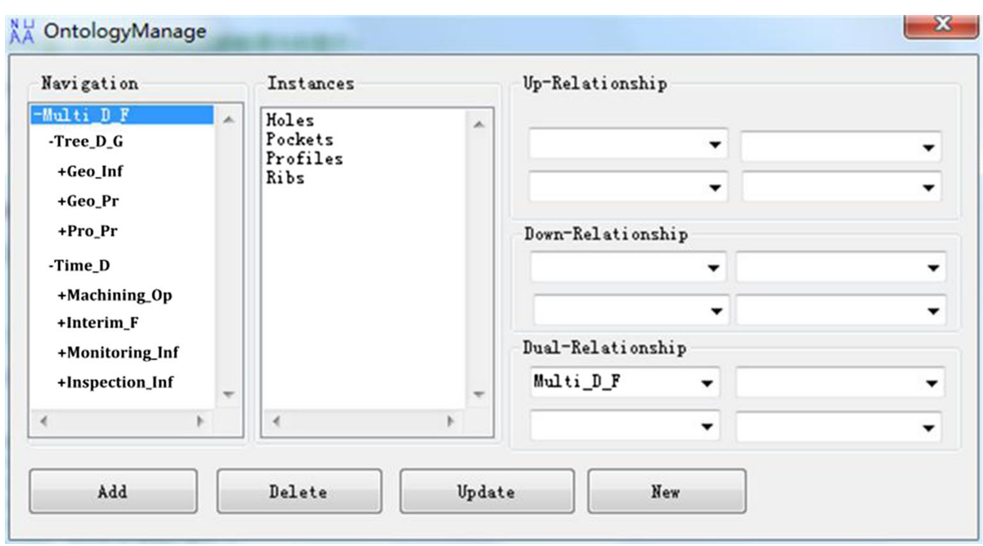


Fig. 8 Ontology management interface

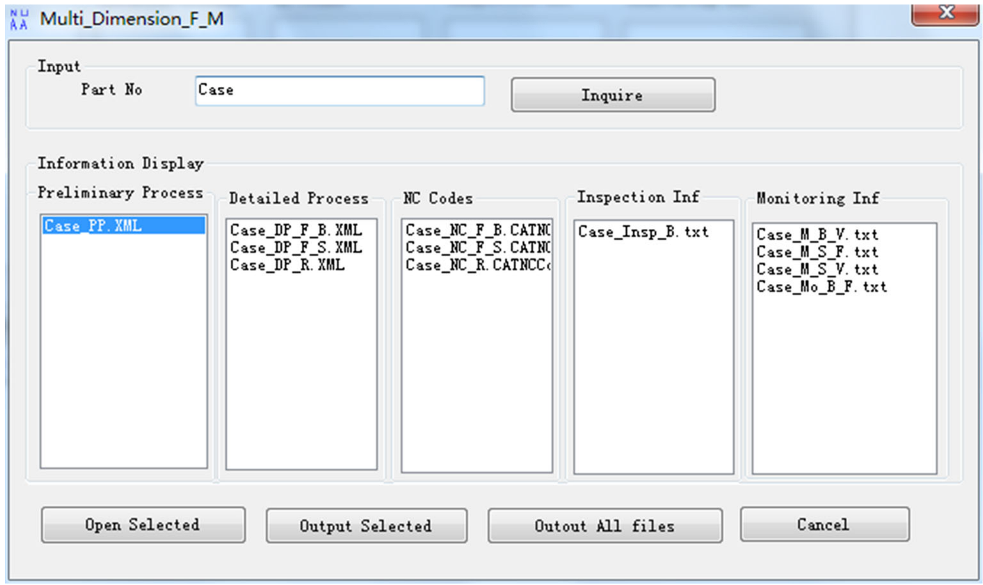


Fig. 9 Multi-dimension feature management interface

preliminary process planning results, the driving geometries for the machining operations are completed. Take roughing for example, the driving geometries include the driving curves of the pocket boundary, the bottom face, the top face, and check geometries. Here, the interim features are defined according to machining operations. The preliminary process planning results together are output into an XML file. The XML files are all sent to the multi-dimension feature management agent, marked by corresponding keywords.

After the generic process planning, detailed process planning is executed by downloading the previous planning results from the multi-dimension feature management agent, as shown in Fig. 7b. Detailed process planning is completed by considering the availability of manufacturing resources. Please note that if the manufacturing resources change, the process planning is only required to be redone at this stage with very little additional work. Tool path generation, simulation, and verification are completed after then. The detailed process planning results are output into an XML file, and tool paths are output into some NC code files, and all the resulting files are sent to the multi-dimension feature management agent.

At the online stage (as shown in Fig. 7c), if the characteristics of monitoring signals are analyzed as abnormal by the monitoring agent, inspection is required, e.g., for possible deformation of the bottom face. In this experiment, cutting force and vibration signals are collected, and the thickness and surface shape of the machined bottom face are inspected by thickness and position probes. The inspection data are analyzed by the inspection agent. The monitoring information and inspection data during machining process are organized by TXT files, and these files are sent to the multi-dimension feature management agent. The recorded information will be used as reference for selection and optimization of cutting operations and cutting parameters for future part machining.

Figure 8 shows the user interfaces for ontology management. The ontology is organized by hierarchical structure in the navigation, and the classes, instances, concepts, properties, and relationships of ontology can be selected and edited. The instances of multi-dimension features of aircraft structural parts are listed. When the information of the ontology is changed, it can be updated. Figure 9 shows the user interfaces for multi-dimension feature management, where the generic process planning, detailed process planning, NC codes, inspection information, and monitoring information are displayed, and each type of the information can be selected, read, and output.

6 Conclusions

This paper presents an integrated process planning and control method based on intelligent agents and multi-dimension manufacturing features. An intelligent agent-based approach is adopted to realize the intelligence and autonomy of individual software modules, and a multi-dimension manufacturing feature model is established based on ontology to facilitate the integration of process planning and control, as well as to speed up the decision-making of intelligent agents.

The advantages of the proposed approach in contrast to the existing process planning and control methods include the following:

1. The functionality partitioning is optimized considering feasibility and online computational load.
2. The generic process planning results can adapt to changing manufacturing resources availability.
3. The online control module can make decisions autonomously because of the sufficient multi-dimension feature

information and the introduction of autonomous software agents.
4. The machining process information can be fed back to improve future process planning quality.

The implementation results based on the proposed method show that it is feasible to achieve integrated process planning and control based on intelligent agents and multi-dimension manufacturing features. Our short- to medium-term future work includes the following:

1. Conducting case studies in a real manufacturing enterprise and further developing the prototype system to accommodate real machining conditions
2. Further developing distributed process planning algorithms aiming at addressing online machining issues and unexpected events
3. Improving the triggering mechanisms from monitoring to inspection so as to enhance the intelligence of the manufacturing system

As real-time monitoring signal processing involves tremendous data analyses, Big Data technology will be utilized to speed up the monitoring data processing and analytics-based decision-making. On the other hand, a cloud automation approach has also been considered for distributed manufacturing process information storage and sharing.

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