



# An intelligent CNC controller using cloud knowledge base

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## Abstract

CNC machine tool plays a vital role in intelligent manufacturing, but up to now, CNC controller, which works as the “brain” of the machine tool, is just a loyal executor of machining command without intelligence. This paper is aimed to improve the intelligence of CNC controller from the aspect of machining process planning, which has a great effect on product quality and production efficiency. A STEP-compliant data model is adopted. Compared to previous STEP-NC controller, this paper presents a new paradigm to integrate the ability of autonomous process planning into CNC controller based on cloud knowledge base. A hierarchical and modular architecture is designed to obtain machining process planning from cloud knowledge base timely and to conduct the machining implementation on shop floor. Furthermore, efficient and matching operation mechanism is researched. It offers a proposal to use cloud knowledge to implement intelligent manufacturing. Finally, a case study is demonstrated to verify the feasibility of this intelligent CNC controller.

**Keywords** Intelligent CNC controller · Cloud knowledge base · Machining process planning

## 1 Introduction

Driven by the development of information technology and network technology, intelligent manufacturing shows its superiority over traditional manufacturing modes and is considered to be the most promising industrial manufacturing mode in the future. Computer numerical control (CNC) machine tool at the end of the entire numerical manufacturing technology chain, directly facing the actual processing and production, is the basic equipment of intelligent manufacturing. Furthermore, the CNC controller acts as the “brain” of the machine tool. Its performance greatly determines the quality and production efficiency of the product. However, at present, the CNC controller in used is just a loyal executor of machining command without intelligence, which greatly impedes the realization of intelligent manufacturing.

Along with the tendency of customized manufacturing, the product becomes more and more complicated, which leads to the prolongation of production preparation cycle and more uncertainty of product quality. In order to shorten the time of preparation, it is urgent to improve the intelligence of CNC controller, especially from the aspect of machining process planning which occupies a large part of production preparation cycle. However, a lot of machining experience is needed to be accumulated in process planning. It is difficult to achieve automatic planning just according to various algorithms. In recent years, the booming information and network technologies gradually penetrated into every corner of the society, having tremendous effects on production and economy of society. Cloud computing has been applied in the manufacturing field. Then, a new concept called cloud manufacturing is presented and widely researched by Tao et al. [1, 2] and Wang et al. [3]. Cloud computing provides the ability to store and process big data with the feature of high efficiency and high flexibility, which points out a new direction to deal with the burdensome task in machining process planning. Cloud knowledge base technology based on cloud computing makes it possible to integrate autonomous machining process planning into CNC controller [4]. However, there are still several points for CNC controller working as an executor to be considered on the purpose of achieving intelligent process planning listed as below.

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- Compatible ability to exchange information with upstream such as CAD, CAPP, and CAM systems
- Real-time ability to search and obtain machining process planning solutions from cloud knowledge base
- Ability to deal with machining process planning solutions in cloud, and then to conduct the machining implementation

This paper presents a new intelligent CNC controller using a machining process planning system based on cloud knowledge base, which can be viewed as the next generation of intelligent machine tool controller. Knowledge in cloud knowledge base is organized according to a STEP-compliant machining data model. This research focuses on the structure and operation mechanism of intelligent controller with the ability to do machining process planning itself, giving response to the machined task in time. In Section 2, related work about intelligent CNC controller is reviewed. The concept of intelligent CNC controller using cloud knowledge base including structure and detailed implementation method and using method is introduced in Section 3. The feasibility of the controller is demonstrated through a case study in Section 4. Section 5 discusses the advantages of this controller. Finally, Section 6 gives a conclusion and the future work is analyzed.

## 2 Related work

In order to achieve the intelligent goal of CNC controller, a lot of effort has been put in this field. In this section, we review the related researches, especially from the aspects of machining knowledge data model and machining process planning.

### 2.1 The state-of-art of intelligent CNC controller

The original machining data model ISO 6983 (G-code) that has been used in CNC controller since the 1950s has limited and less compatible information, which results in that controller cannot have a full understanding of machining task and machining requirements to implement intelligent operations. To overcome the shortcoming of the old standard ISO 6983, a new object-oriented international standard ISO14649 (STEP-NC) was built since the 1990s, which contains more enriched information including geometry, machining technology, machining strategy, and cutting tool for machined parts [5, 6]. Meanwhile, STEP-NC is compliant with STEP, so it makes the seamless information transmission among CAD, CAM/CAPP, and CNC chain possible. Xu et al. pointed out that STEP-NC-enabled controllers would achieve distributed interoperable intelligent manufacturing, and the challenges and opportunities ahead are analyzed [7].

Along with the establishment of high-level, informative, and interoperable data model, some researches have been presented to guide the implementation of intelligent CNC controller. On the utilization of STEP-NC data model, Wang et al. suggested a “Plug-and-Play” function block-based CNC system that adopts indirect methods to translate STEP-NC data to G-code through the mapping mechanism [8]. A STEP-compliant NC converter (called STEPcNC) is developed by Xu. A STEP-NC file as the input is accessed to STEPcNC converter, and 6K program, a native programming language code, is output to the retrofitted lathe [9]. Strictly speaking, the converter or translator in this kind of controller server as “post-processor” on conventional CNC and controllers in this type are mainly used to prove the feasibility of STEP-NC standard without any more intelligence, compared with conventional CNC using G-code.

Suh et al. presented a paradigm for intelligent CNC using ISO 14649 interface scheme, which is based on the analysis of requirements. The conceptual architecture of this intelligent CNC is composed of SFP/TPG modules that undertake shop floor programming and tool-path generation, control modules that are responsible for task management and implementation, and common data base modules that store data to support SFP/TPG modules and control modules [10]. Based on the architecture mentioned above, an enhanced framework, autonomous STEP-compliant CNC (called ASNC) is presented by the authors. In addition to more intelligent modules or functions, such as a scheduler for workingstep, update of toolpath, and a monitor, the requirement of open architecture for implementation in industry aspect is analyzed. [11]. In the subsequent researches, a relatively complete STEP-compliant intelligent CNC Korea STEP-NC is built, which is supported by databases, and the internal modules of intelligent CNC controller communicate with each other via CORBA protocol. [12]. Then a STEP-compliant system TurnSTEP with three subsystems, Code Generation System (CGS), Code Editing System (CES), and Autonomous Control System (ACS), is presented for turning machining. It intends to improve the autonomy of control system from the aspect of recovery from abnormal situations based on STEP-NC data model [13].

In order to deal with rapidly changing customized product requirements in a distributed environment, Allen et al. presented a process planning system based on multi-agent technology to generate STEP-NC file [14]. Nassehi et al. recognized and extended the earlier research; a multi-agent process planning system, MASCAPP, is presented with object-oriented database being selected to store supporting information [15].

These researches were mainly focused on a bidirectional information flow between upstream systems and CNC controller, which contributes to the portability and interoperability of the whole manufacturing system. And we can see that it is a tendency that the intelligent controller is

developed into an integrated system. But there are still some obstacles in some aspects such as machining knowledge data model and machining process planning, to practical applications in industrial factories.

- Despite the basic information, the machining knowledge data specified in STEP-NC is not perfectly suitable for autonomous process planning to be integrated in intelligent CNC controller. Because it lacks adequate machining requirement to make CNC controller have a comprehensive understanding of workpiece. And the existence of special machining information such as workingsteps and machining strategies places restrictions on the decision-making and process planning ability of intelligent CNC controller itself.
- Machining process planning plays an important role in converting a raw piece to a finished part according to the specification set given in design phase and resources available. However, the machining process planning of the controllers reviewed above is far from enough, which is limited in workingstep sequence adjustment and machine parameter optimization by operators. Meanwhile, the hardware equipment that carries the controller has limited computing power to implement high-quality process planning.

## 2.2 Previous work

On purpose to solve the problems mentioned above in intelligent CNC controller, our research team has done a series of work, which is briefly introduced in this part.

### 2.2.1 Machining knowledge data model

To solve the problems about machining knowledge data model, our research team proposed a machining knowledge data model to provide necessary information for intelligent CNC controller to carry out machining process planning. The machining knowledge data model is composed of machining task, machining process planning, and machining resource. And the instances of these three parts are supposed to be stored separately. Machining task is clearly represented through rawpiece, manufacturing features, and machining requirement of the workpiece, which is designed as an Application Reference Model (ARM) [16]. Machining process planning describes the feature, operation, and cutting tool for each work step in sequence. Moreover, the machining resource is built to describe the machining ability of machine tools. Specially, machining requirement like geometric tolerance and surface texture is modified or added in the machining task part.

On purpose of organizing the complicated concepts, relations, and property in machining knowledge data model and making intelligent process planning suitably, ontology technology is chosen to build knowledge model. Ontology is of the abilities that express the semantic of machining information explicitly and make the machining information readable and understandable by computers. And then it contributes to the sharing and reusing of information. The ontology edition software protégé is chosen to build this knowledge data model with Ontology Web Language (OWL) and finally expressed in the XML format.

### 2.2.2 Machining process planning

Machining process planning is a knowledge-intensive activity, no matter what kind of intelligent algorithms (fuzzy logic [17], neural network [18], colony algorithm [19], genetic algorithm [20]) or rule-based expert systems [21] are adapted, they are not able to deal with massive and ever-increasing knowledge. Meanwhile, it is also difficult for an intelligent controller with an off-line machining process planning system to make a timely and accurate decision without knowing the actual status of the machine tool at shop floor level.

Based on cloud technology, our research team developed a machining process planning system based on cloud knowledge base for intelligent CNC controller to solve the problems mentioned in Section 2.1 [22]. It consists of five modules including database, query engine, reasoning engine, and two file dispose modules. The database on HBase is designed to store and manage the massive and ever-increasing machining process knowledge instances, which contains two tables for workpiece and solution separately. Query engine and reasoning engine, which are based on Map/Reduce computational paradigm, are used to generate the optimized solutions according to task and resource files with rapidly distributed and parallel processing ability. Two dispose modules are capable of organizing input and output files in the format as required. Knowledge instances satisfying certain format requirements can be collected by the Internet, and the knowledge reasoned by knowledge base itself is also stored as instances. Benefitting from the enhanced capability of distributed storage, the collection of knowledge is open. The more knowledge is shared, the better the performance of cloud knowledge base is.

The machining knowledge data model in Section 2.2.1 and machining process planning system in Section 2.2.2 lay the foundation to achieve intelligent CNC controller. Yet, there is still a need to design suitable framework of intelligent CNC controller to communicate with cloud knowledge base and to adopt efficient operation mechanism to implement the solutions of process planning got from cloud, which are the focuses of this article and will be introduced in the following.

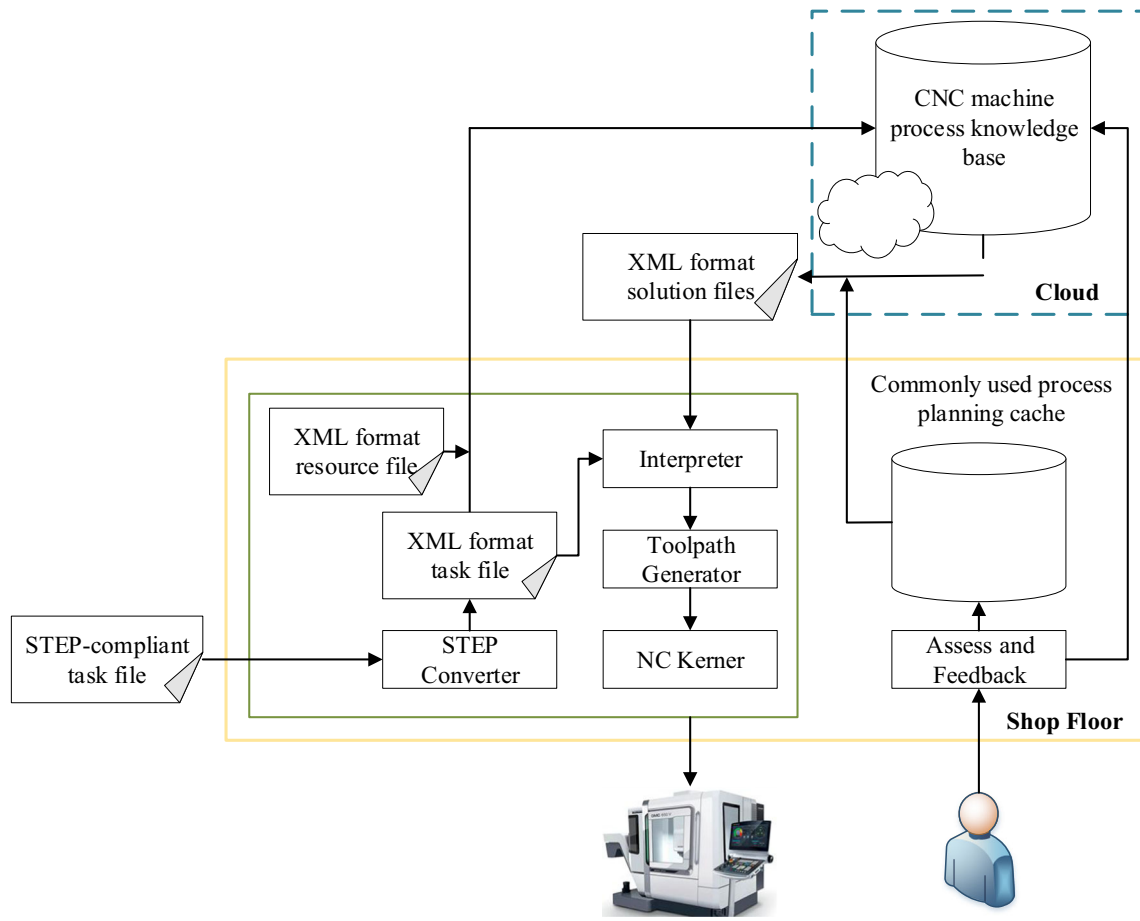


Fig. 1 Framework of intelligent controller

### 3 Concept of intelligent controller using cloud knowledge base

This section is aimed to the application and quick acquisition of knowledge in cloud and decision-making online. Several intelligent modules are designed, and more modules needed can be integrated easily.

#### 3.1 Structure

As illustrated in Fig. 1, the structure of this intelligent controller can be decomposed into two layers. The upper layer in cloud contains a machining process planning system

based on cloud knowledge base mentioned in Section 2.2.2. It is in charge of giving the machining process planning for machined parts in time. The machining knowledge is stored in a data structure in accordance with STEP to guarantee the compatibility to exchange information with upstream, and the data structure makes it possible that problems reflected during machining could be fed back to improve machining process planning solution at the design stage. The lower layer is designed in a modular method with a scalable feature. It is responsible for communicating with knowledge base in cloud and controlling the machine tool on native shop floor. Information that fed to controller is not just the motion instructions anymore, which has a more

Fig. 2 STEP converter and interpreter module

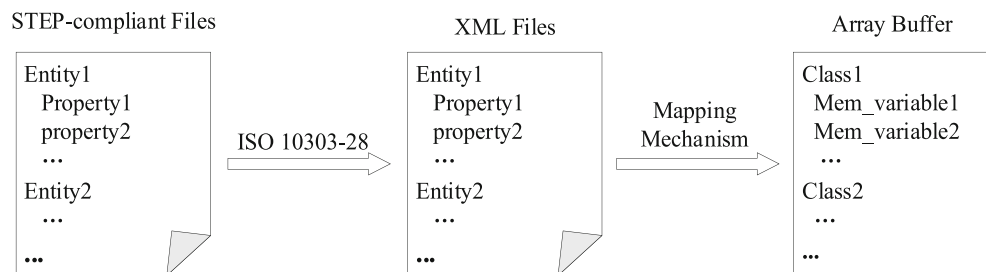
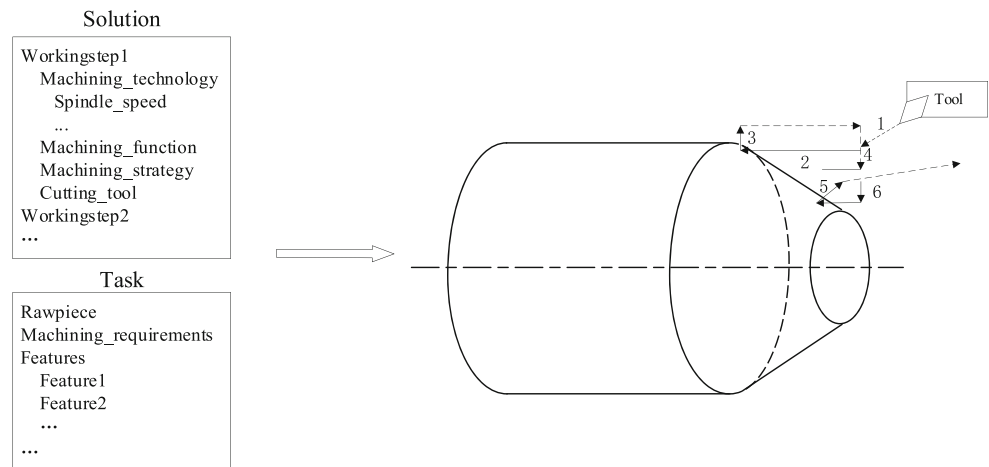


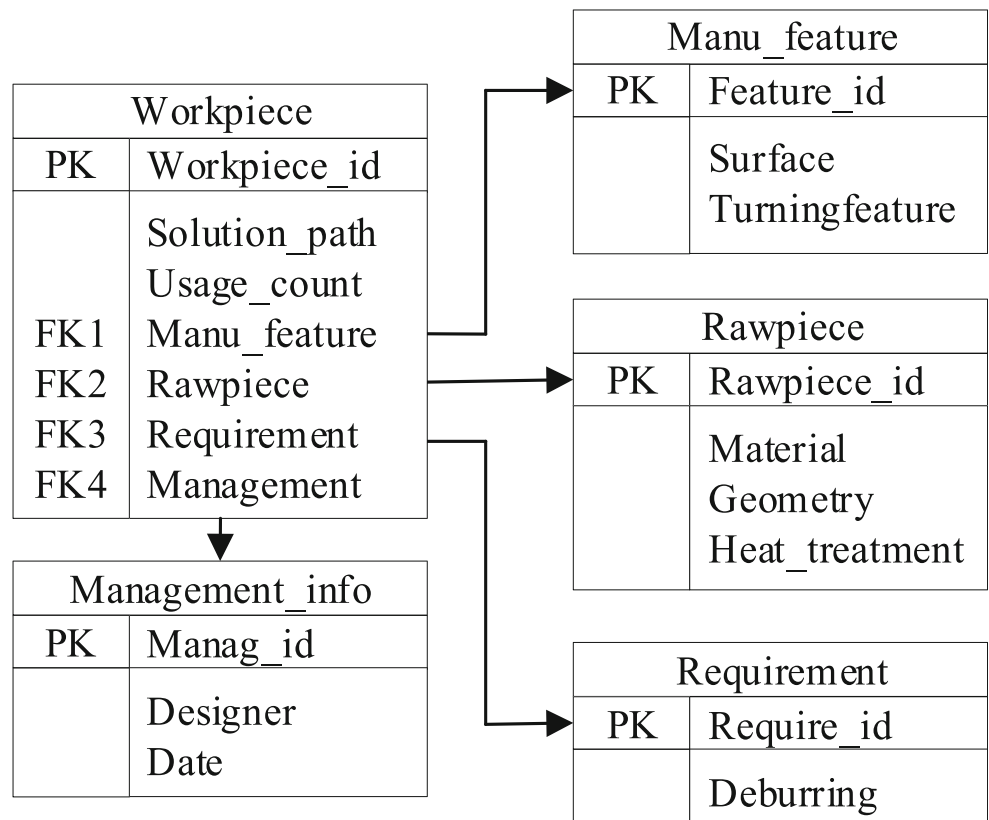
Fig. 3 Toolpath generator module



complicated data structure and cannot be directly used by NC kernel. So a STEP converter is designed to preprocess the STEP-compliant task file input. Interpreter and toolpath generator acting as two basic modules work cooperatively translating the physical files received into internal format and sending the data to NC kernel to control the machine tool. A commonly used process planning cache is designed to promote the quick acquisition of knowledge. And an assessment module is used to filter the low-quality knowledge and give feedback to knowledge base in cloud.

These two layers communicate with each other through transferring files by the Internet. The lower layer is works as the client to submit the task file and resource file that specify the part to be machined and the machine tool available respectively to the upper layer. The file submission function is embedded in the native controller, which is encapsulated as API. Namely, the operators should submit the task file and resource file to the native controller, the interface between the upper layer and lower layer is not open to users. The information contained in files abides by the machining knowledge data

Fig. 4 Basic tables of commonly used process planning cache



model mentioned in Section 2.2.1. Generally speaking, the resource file of a machine tool needs no modification unless the tool magazine has been changed. And the upper layer is working as the server to receive the files from the lower layer and to send the solution file that depicts the corresponding machining process planning for machined task to guide the machining process on shop floor.

### 3.2 Intelligent modules

#### 3.2.1 STEP converter and interpreter module

The task file generated from upstream is usually in STEP-compliant format described in EXPRESS language, which causes obstacles to share on the Internet. So a STEP converter is designed to translate STEP-compliant physical file into XML schema neural file according to ISO 10303 Part 28, which is illustrated in Fig. 2. Because XML is interoperable, extensible, and shareable, it is perfectly suitable for network transportation.

The main function of the interpreter module is to retrieve the contents of the files, extract the processing-related information, and then store the information data in accordance with a certain data structure for subsequent processing and calculation. The data structure in XML files is inherited from STEP-NC, which is similar to the object-oriented definition of class in C++ programming language. Therefore, the mapping mechanism between data structure in XML file and class in C++ is built by the relations such as inheritance and polymorphism. As shown in Fig. 2, the instances of classes in C++ are used to store the instances of entities in STEP-NC. And the values of properties of entities are assigned to the member variables of classes. Finally, the interpreter translates the input files into C++ array buffer according to the mapping mechanism.

#### 3.2.2 Toolpath generator module

The toolpath in STEP-NC is optional, so does it in XML scheme, which enhances the intelligence and openness of controller to some extent. Thus, a toolpath generator becomes an indispensable module for controller implementation on shop floor. A general method of tool-path generation is presented here, and more efficient strategy will be developed and adapted in the following work. As shown in Fig. 3, the solution part of machining procedure is divided into a series of workingstep. Workingstep, as an executable, describing the machining technology (spindle\_speed, feedrate, etc.), machining function (coolant, chip\_removal, tail\_stock, etc.), machining strategy (unidirectional, bidirectional, etc.), and cutting tool, along with the geometry of feature in task file provides enough

information to generate tool trajectory. And thus, the process of machining task is also organized according to the sequence of workingsteps. The output data of toolpath generator is in the format that can be directly recognized by the NC kernel.

#### 3.2.3 NC kernel

To control the motion of machine tool, an NC kernel is required. Several components such as interpolator, acceleration/deceleration controller, and position controller are constructed with basic algorithms. Data received from toolpath generator is processed in NC kernel, and translated into motion control signals to servo and I/O board via field bus.

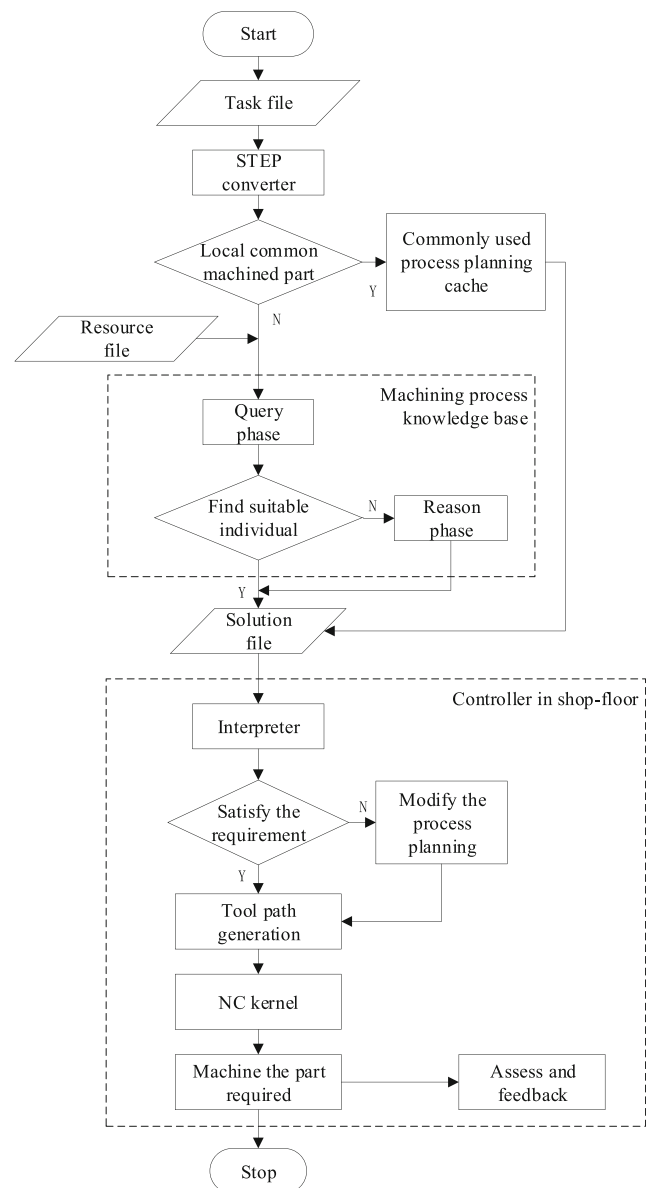


Fig. 5 Workflow of intelligent controller

**Fig. 6** Submit files and receive solutions

Received Solution

	File name	IP	File size	File date
0	solutionfile1	219.231.147.51	4767	20171030143125
1	solutionfile2	219.231.147.51	4782	20171030143125
2	solutionfile3	219.231.147.51	4813	20171030143125
3				
4				

Knowledge query

**task file**

**resource file**

Knowledge submit

**knowledge file**

### 3.2.4 Commonly used process planning cache

In order to guarantee the quick acquisition of machining process knowledge and improve the machining efficiency, a commonly used process planning cache is designed in native

controller, which is regularly updated according to the frequency of process planning called.

When task and resource files are submitted to knowledge base in cloud, one or several corresponding solution files that satisfy the machining requirements would be

**Fig. 7** Detail of machining process planning

**Workingstep** 0 ▼

Feature&Tool

Feature

Tool

Turning\_technology

Spindlespeed  r/min

Feedrate  mm/r

sync\_spindle\_and\_z\_feed

Machine\_function

Coolant

Chip\_removal

Tail\_stock

Steady\_rest

Follow\_rest

Machine\_strategy

Strategy

Cutting\_depth  mm

Start\_point

Variable\_feedrate  mm/r

Feed\_direction

Back\_path\_direction

Lift\_direction

Lift\_height  mm

Lift\_feed  mm/r

Stepover\_direction

Stepover\_feed  mm/r

Overcut\_length  mm

Allow\_length\_passes

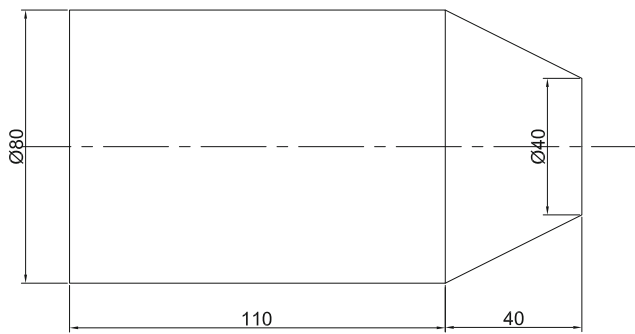


Fig. 8 Example workpiece

sent back to the controller. And the solution file selected by the operator to implement the machining operations and the task file depicting machined part would be stored in a native controller. As the cache is designed in an industrial personal computer with embedded operating system, SQLite is adopted to implement this knowledge cache for its portability, flexibility, and high-efficiency processing small-scale data.

Several basic tables of database are shown in Fig. 4. Tables for the workpiece/manufacturing feature/rawpiece/technological requirement/management information are based on their corresponding classes. Subclasses and properties are added as fields to their corresponding tables respectively. The information in solution files are not contained in data base, but its storage path is set as a field of the table workpiece.

- Table for the workpiece. This table is the parent table of others. Workpiece\_id uses system time and a random number as the seed to guarantee its uniqueness. Usage\_count increases with the increment of the frequency of the file called.
- Table for manufacturing feature. This table consists of information about geometry of the workpiece, dimension, tolerance, surface, and so on.
- Table for rawpiece. This table is designed based on geometry, material, and heat treatment information of rawpiece.
- Table for technological requirement. Other requirements not mentioned above for example deburring are contained in this table.
- Table for management information. Fields include the designer and design date.

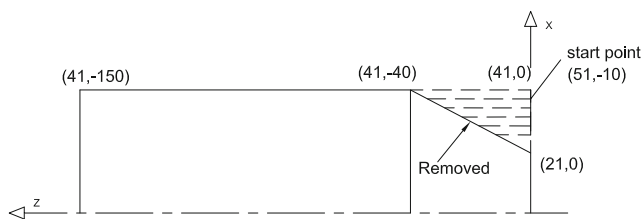


Fig. 9 Start point of workingstep 3

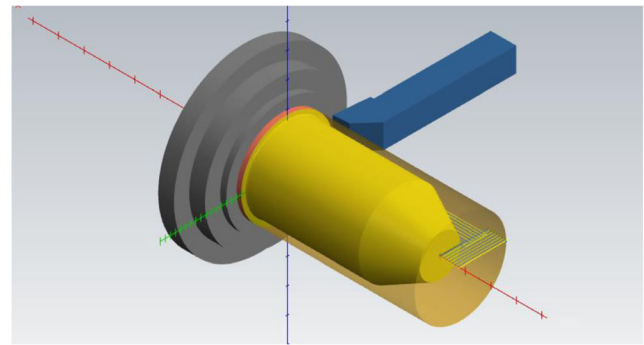


Fig. 10 Simulation of machining process

### 3.3 Using method

Along with the suitable structure built to interface with cloud knowledge base, it is supposed to adopt efficient and matching operation mechanism. The workflow is illustrated in Fig. 5. At first, the task file as an ARM is input into controller on shop floor and converted into XML format. Then the controller checks whether the machining task is a commonly used workpiece. If the corresponding solution file has already existed in the native controller, it will be transmitted to the interpreter directly. If not, the task file and resource file in XML scheme are submitted to machining process knowledge base in cloud via the Internet (Fig. 6). The query engine begins to search for feasible machining process planning according to the submitted files through mapping mechanism. If there is no available individual, reasoning engine works subsequently. The solution files as output of knowledge base are sent to the controller on shop floor via the Internet. The operator can choose the solution file needed and the detail information of machining process is presented (Fig. 7). Proper adjustment of parameters is allowed according to expert's experience, and it would be saved as a new solution file. In the interpreter module, data in the task file and solution file is analyzed and encapsulated in a buffer for processing in the tool-path generation module. Then, the target part would be machined based on the machining process planning information. When unexpected faults such as a tool breakage occur, an alternative machining process planning from received solution files would be carried out. Finally, the operator is supposed to evaluate the machining process planning that had been applied in light of the actual effect such as machining efficiency, production quality, energy consumption, and so on. Then the evaluation result is fed backed to knowledge base in cloud to contribute to the filter of low-quality knowledge and the work of query engine and reasoning engine. And the operator is also encouraged to share the proven high-quality machining knowledge about process planning to knowledge base



(Fig. 6). This operation mechanism enables online decision-making of process planning to be a reality and improves the autonomy of intelligent CNC controller to a certain extent.

## 4 Case study

On the shop floor, the implementation methodology, soft PLC + real-time industrial Ethernet, is adopted to achieve the open, interoperable, and extensible goal of hard devices. Just following the same real-time industrial Ethernet protocol, controllers are capable of communicating and exchanging data with devices produced by different suppliers. And hard devices such as servo motor and I/O can be appended or removed as requirements. Meanwhile, it enables better information integration capability with the upper layer in cloud to make full use of the superiority of machining process knowledge base.

The real-time industrial Ethernet, EtherMAC, proposed by our lab is applied to communicate with underlying hardware devices, which ensures better network communication and data processing capabilities with open and flexible features. EtherMAC performs well in the field of real-time synchronous movement control without relying on hard real-time operating system.

The example workpiece depicted in the task file is shown in Fig. 8. It is made up of three features, two outer\_diameter and one end\_face. The solution file contains mostly process parameters and all machining strategies; some parameters are decided on native controller or use default values. For example, as shown in Fig. 9, the start point for the third workingstep of example workpiece is (51, -10), which is 10 mm away from the endpoint (41, 0) in the X direction and the Z direction, respectively, if the start point is not set up manually.

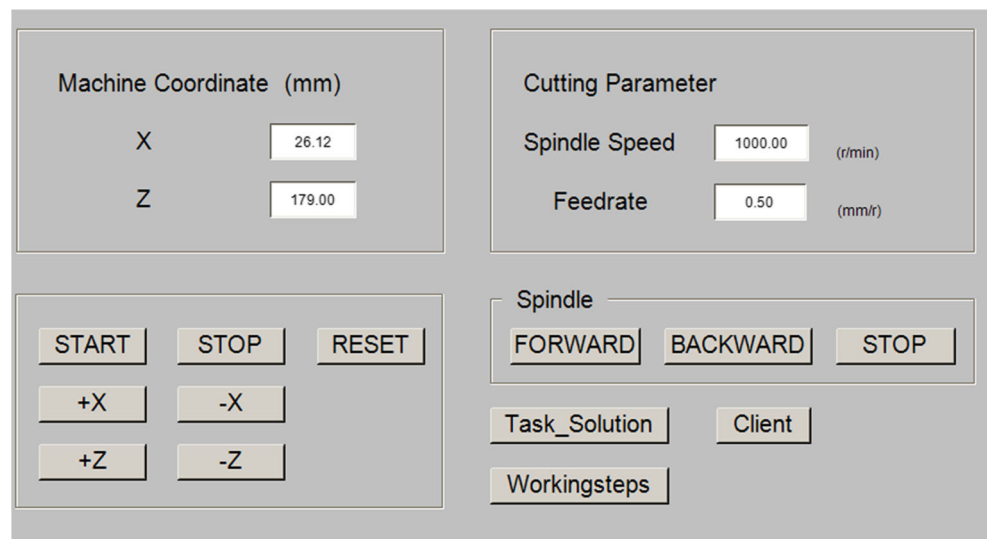
The example workpiece shown in Fig. 8 is machined to validate the feasibility of this intelligent CNC controller. It is executed on a 2.5D turning machine tool with an intelligent CNC controller we developed. The simulation result of the machining process is shown in Fig. 10. Figure 11 pictures the control interface of this case study.

## 5 Discussion

Compared to traditional CNC controller, the advantages of the intelligent CNC controller using cloud knowledge are listed below:

- Machining knowledge data model. In this paper, the data model with rich semantics is adopted to provide CNC controller with comprehensive machining information knowledge, which is the basis of intelligent implementation paradigm. Meanwhile, it enables the seamless and interoperable information translation in CAX chain for that the data model is compliant with STEP.
- Collaboration and sharing. The accumulation of machining knowledge is a collaborative activity among companies, communities, even the whole manufacturing industry. The participant shares their machining knowledge and assesses the process planning to improve the quality of solutions.
- Efficiency. The users are able to acquire high-quality solutions across the constraints of time and space. And the non-machining time is greatly shortened. Thus, the efficiency of machining will be improved significantly.
- Autonomy. This intelligent CNC controller is an open and integrated system with the ability to do process planning timely on shop floor. To some extent, the online decision-making ability of controller is improved.

**Fig. 11** Interface of machining process



- Servitization. Machining process planning is provided to users as a service, benefitting from the technologies cloud computing, big data analytics, and so forth. It accords with the concept “Manufacturing as a service” [23], which is considered the development trend of an advanced manufacturing field.

## 6 Conclusion and future work

In this paper, a new intelligent CNC controller with a hierarchical structure is presented. On the upper layer, the machining process planning system using cloud technology is applied. It works as the brain of this CNC controller to offer intelligence supporting with the ability to do query task and reasoning task in parallel and distributed processing method, which greatly enhances the processing efficiency of massive knowledge. Since the knowledge stored in HBase is compliant with STEP, this structure enables the seamless information translation with upstream to ensure the openness and intelligence from the perspective of the data model.

The lower layer is developed in a modular method. Two basic modules, interpreter and toolpath generator, are developed to take advantage of the enriched information got for intelligent manufacturing. Commonly used process knowledge cache improves the efficiency of production. It submits the task file to the upper layer in cloud via the Internet and executes machining operation according to the machining process planning solution got from the upper layer. The adoption of modular implementation method can guarantee flexible combination and customized development. Besides the modules have been developed, more intelligent modules can be integrated conveniently with the same way. And the hardware devices can be added or removed as needed, which benefits from flexibility and extendibility of industrial Ethernet.

Compared to previous STEP-NC controllers, this new intelligent CNC system gathered the knowledge of machining process experts with the help of cloud knowledge base. It offers a proposal to use cloud knowledge to implement intelligent manufacturing. Intelligence and decision-making are gathered in the controller with the collaboration of cloud knowledge base. The autonomy of intelligent CNC controller is improved. Meanwhile, the non-machining time is greatly shortened.

This project focuses on improving the intelligence of CNC controller from the aspect of machining process planning. But in actual, the production implemented on CNC machine tool is a complicated and interoperable activity, thereby the intelligence of CNC controller includes, but is not limited to, machining process planning. The other aspects such as fault prediction, scheduling and the collaboration of several machine tools, and so forth will be researched in future work.

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