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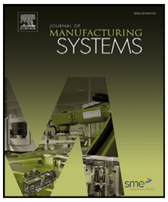

Technical paper

# STEP-NC enabled edge–cloud collaborative manufacturing system for compliant CNC machining

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ABSTRACT

In recent years, edge–cloud collaborative manufacturing systems have been applied to achieve accurate data tracking and intelligent machining analysis in the field of CNC machining. However, due to the lack of other dimensional tags, such as workstep and speed, which are related to process data, the current systems are still at a level of processing time-tag machining data. It is of great significance to address the problem of linking actual machining data with other dimensional tags, which can achieve more accurate and intelligent data interaction between design and manufacturing. This paper proposes an edge–cloud collaborative manufacturing system based on STEP-NC, which enables the exchange of machining data tagged by workstep, improves the accuracy of data traceability, and lays the foundation for more intelligent processing analysis. Especially, a method of dynamic task delivery and data subscription according to the environment is proposed to improve the manufacturing system's two-way data flow interaction ability. On the basis of that, a manufacturing information segmentation method based on workstep is proposed, which makes it easier to sort information from the coupled data. In addition, the system is compatible with heterogeneous CNC machine tools to achieve large-scale industrial applications. Finally, a prototype system has been installed in a workshop located in COMAC, and corresponding experiments are carried out on the CNC machine tool for COMAC parts manufacturing, which verifies the feasibility of the proposed method.

## 1. Introduction

In recent years, the research interest in manufacturing data tracing and processing analysis is an effective way to improve machining efficiency, reduce cost, and ensure the quality of parts [1,2]. Using edge–cloud to solve this problem is one of the cores of CPS, digital twin, and other manufacturing systems. Morgan and O'Donnell developed an online monitoring system for CPS processing data, which uses multi-sensor fusion technology to enable online monitoring of machine tools through data cleaning and data classification [3]. Liu et al. [4] proposed a kind of machine tool digital twinning system for machine tool state data acquisition and monitoring. Tong et al. [5] proposed a real-time processing data application and service based on machine tool digital twinning to implement manufacturing data visualization and analysis. Zou et al. [6] developed the edge intelligent gateway system. They designed the cloud edge collaborative service framework for the perception and access difficulties of massive heterogeneous manufacturing resources in the cloud manufacturing and service system. Wang et al. [7] proposed a CNN-based element segmentation algorithm that supports edge–cloud collaboration for flexible manufacturing systems to classify part models accurately. Jamshidi and Budak [8] designed an optimization of grinding parameters based on digital twinning technology to improve machining quality and efficiency. The manufacturing systems utilized in the aforementioned study all employ G codes as the interaction standard, resulting in the collected machining data being processed with time-tag. This occurs because G codes only contain information pertaining to tool paths, lacking essential process information such as worksteps and tools. Consequently, the extensive collected machining data becomes intertwined. This means optimizing current artifacts requires people to spend a lot of time sorting out useful information from the coupled multivariate data collected by the system. Therefore, the information format of the G code is weak, resulting in data flow tracing and process analysis still at the primitive level.

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**Nomenclature**

| | |
|---|---|
| AIM | Application Interpretation Model |
| API | Application Programming Interface |
| ARM | Application Reference Model |
| CAA | Component Application Architecture |
| CAD | Computer-Aided Design |
| CAM | Computer-Aided Manufacturing |
| CAPP | Computer-Aided Process Planning |
| CNC | Computer Numerical Control |
| CNN | Convolutional Neural Network |
| COMAC | Commercial Aircraft Corporation of China, Ltd. |
| CPS | Cyber Physical System |
| DJI | Shenzhen Dajiang Innovation Technology Co., Ltd |
| DNC | Distributed Numerical Control |
| OPC UA | OPC Unified Architecture |
| PosSFP | Pos Shop Floor Programming |
| R&D | Research and Development |
| STEP-NC | Standard for the Exchange of Product model data - Numerical Control |
| STEP | Fluid–structure interaction |

To solve the problem of the weak format of processing information, researchers call for the use of more informative standards. STEP-NC instead of G/M code is considered to be one of the solutions to the above problems [9]. According to Xu et al. [10] and Suh et al. [11] the STEP-NC provides a new data interface for the data stream of CAD-CAM-CNC and is considered to be the programming language for the next generation intelligent CNC. At present, there has been a lot of research on the STEP standard to achieve effective tracking of manufacturing data and more intelligent process optimization. Xiao et al. [12] proposed a complete CAD/CAM/CNC machining solution conforming to STEP and a complete Step-compliant solution based on CATIA secondary development platform combined with EtherCAT bus technology. Kubota et al. [13] combined STEP-NC with digital twinning technology to propose a more intelligent manufacturing information interaction framework. Zhang et al. [14] adopted an artificial bee colony algorithm combined with a back-propagation neural network to implement STEP-NC-based manufacturing intelligence feature recognition. Ridwan and Xu [15] proposed a feed rate optimization algorithm based on STEP-NC and distinguished between rough and fine machining. With cutting force and cutting power as constraints, the fuzzy algorithm was used to detect and analyze the cutting state, and the cutting parameters were constantly optimized. Zhang et al. [16] predicted workpiece surface roughness using side-edge Angle, end-edge Angle, tool tip radius, and feed speed in STEP-NC high-level information, and generated turning tool rails online according to the STEP-NC file.

Although there have been many studies on STEP - Compliant and STEP-CNC systems for the feasibility of STEP-NC execution systems [10], the current manufacturing enterprises still do not use STEP-NC as a standard for parts production. Table 1 also indicates that within the present CNC machining requisites, STEP-NC machining excels over traditional methods in numerous aspects. Due to the traditional STEP-NC solution for CNC machining with low intelligence and low efficiency [17], it is difficult to support the needs of manufacturing enterprises. The intelligent and STEP-NC-compatible CNC systems are still in the R&D and test stage without any broad applications. It seriously hinders the development of intelligent numerical control technology in manufacturing data tracking and processing analysis.

Fig. 1 delineates the comparison between a conventional edge–cloud collaborative system and an edge–cloud collaborative system that supports STEP-NC. With the development of edge cloud collaboration technology, it is now possible to establish a connection between the process design end and the CNC machining end. In light of this, if processing information can be exchanged in a standardized data format and segmented based on the worksteps, its accurate traceability and intelligent analysis can be achieved. From this perspective, the issues mentioned earlier will be simultaneously resolved. With the development of edge–cloud collaborative technology [18], if the manufacturing information can be connected with the design of upstream technicians and the processing of downstream CNC machine tools in a unified format, and the processing data and worksteps are combined, the communication of task delivery and data acquisition can be carried out through edge–cloud collaborative technology. Then the process personnel can be able to collect the processing data for accurate traceability and intelligent analysis. From this perspective, the previously mentioned problem would be solved simultaneously.

In this paper, we establish an edge–cloud collaborative manufacturing system that supports STEP-NC, facilitating precise data tracking with intelligence and efficiency. It is mainly reflected in (1) dynamic task delivery and data subscription. (2) Manufacturing information segmentation based on worksteps. (3) Compatible with heterogeneous commercial CNC machine tools to achieve large-scale industrial applications. The structure of this article is as follows: Firstly, the second section briefly reviewed solutions for STEP-NC compatible manufacturing systems and outlined the advantages of edge–cloud collaborative systems, discussing the challenges of supporting STEP-NC in edge–cloud collaborative systems. Subsequently, Section 3 elucidates the systematic methodology of the edge–cloud collaborative system conforming to the STEP-NC. Moving forward, Section 4 exemplifies the application of the proposed manufacturing system through industrial case studies. Section 5 explores the merits of manufacturing systems and offers insights into potential future advancements. Finally, Section 6 presents the drawn conclusions based on the findings.

## 2. Literature review

The STEP-NC is further divided into two standards: ISO 10303 AP238 (AIM Application Interpretation Model) and ISO14649 (ARM Application Reference Model) [9]. This standard allows all systems in CNC machining to use the same "language" while ensuring complete process information [19,20]. We proposed an edge–cloud collaboration solution that supports STEP-NC using the ISO14649 standard.

### *2.1. STEP-compliant manufacturing systems*

The challenges of STEP-NC implementation make it hard to be accepted by both CAD/CAM and CNC vendors [21]. In the past two decades, different researchers have carried out research on manufacturing system solutions with STEP-NC Compatibility from different perspectives. Suh et al. [22] divided the related research into three categories: conventional, integrated, and intelligent. Xu and Newman [20] and Xu and He [21] added a collaborative and distributed STEP-NC CNC system. The development and comparative display of STEP-compliant manufacturing systems are shown in Fig. 2 and Table 2

The conventional type mainly focuses on the research and development of the "poster", which translates STEP AP-203 or AP-204 files into G code format files that can be processed by the current CNC system, so as to implement the processing of parts. STEP Tool has successfully implemented the conversion of STEP AP-203 data into ISO 10303-AP238 files [22,23]. Wang et al. [24] proposed a preprocessor that converts the STEP-NC to G code, which can translate the G code in response to different types of machine tool systems, and achieve compatibility with various CNC systems. This type only interprets STEP-NC information, does not have functions such as data tracing and processing analysis, and is not data closed-loop.

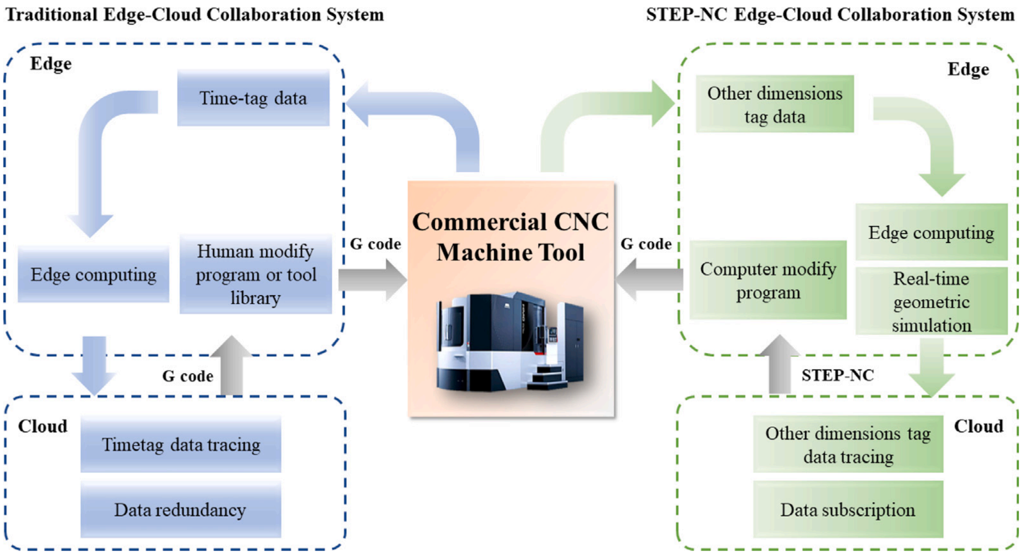


**Fig. 1.** Traditional and STEP-NC edge–cloud collaborative system.

**Table 1**
Comparison of STEP-NC machining and traditional machining in current CNC machining requirements.

| Current CNC machining requirements | Traditional machining | | STEP-NC machining | |
|---|---|---|---|---|
| | Traditional machining | Traditional edge-cloud machining | STEP-NC-Compliant machining | STEP-NC-Compliant edge–cloud collaborative machining |
| Completeness | N | N | Y | Y |
| Hardware dependency | N | N | Partial | Y |
| Interactivity | N | Partial | Partial | Y |
| Traceability | N | Partial | Partial | Y |
| Distribution & collaboration ability | N | Y | Partial | Y |

**Table 2**
Comparison of data tracing and process analysis for different types of systems.

| STEP-compliant manufacturing system | Hardware transformation | Data tracing | Processing analysis |
|---|---|---|---|
| Conventional type | No | No | No |
| Integrated type | Yes | Monitor | Yes |
| Intelligent type | Yes | Monitor/Visualization | Integrated intelligent algorithm |
| Collaborative and distributed type | Yes | Monitor/Visualization/Storage/Trace | Integrated intelligent algorithm |

The integrated type refers to the integration of STEP-NC technology by transforming the hardware of the numerical control system. However, it only has the function of tool path generation and lacks some intelligent functions. Suh et al. [25,26] developed a STEP-NC-based data model and representation for better generation of ISO 14649 part programs. The STEP-NC-based CNC framework ASNC (Autonomous STEP-compliant CNC) was proposed, and the shop floor programming system PosSFP was constructed and validated with milling operations. Latif et al. [27] and other scholars proposed and developed an open CNC system supporting STEP-NC data model based on STEP-NC data interpretation, graphical verification, simulation, monitoring, and reporting of machining information. This type implements the controller's understanding of STEP-NC through the open interface, and it can implement the visualization of partial manufacturing data. It does not have the ability of processing analysis and is also not data closed-loop.

The intelligent type implements some intelligent functions on the basis of the integrated type. Xiao et al. [12] proposed a complete set of CAD/CAM/CNC solutions conforming to STEP manufacturing and developed the corresponding STEP-Compliant prototype system based on TwinCAT. Yusof and Case [28] proposed a STEP CAD/CAPP/CAM system for turning workpiece machining. Ridwan and Xu [29] proposed a machine tool condition monitoring system based on STEP-NC. Some intelligent types can also implement remote control of manufacturing data by combining industrial Internet technology but only process part of the manufacturing data, and the system is in a prototype test state. This type implements simple data closed-loop, with primary-level data tracing and process analysis functions.

To meet the web-based collaborative and distributed manufacturing of parts. Kubota et al. [30] proposed a framework that combines STEP-NC with machine tool digital twin, so that the machine tool can be remotely controlled through its digital twin, enabling STEP-NC processing on standard CNC machine tools without changing the controller. MAZNAH et al. [17] integrated the open architecture of the Internet of Things and the CNC system, which can achieve efficient data collection and real-time information processing, along with process monitoring and feedback. The distributed and collaborative proposal enables design and manufacturing anywhere, but only the transmission and backtracking of static data can be implemented. Konapala and Koona [31] and Konapala and Ramji [32] moved CAD/CAM/CAPP to the web and developed a web-based STEP-NC manufacturing system platform by combining the features of the STEP-NC. This type of network-based improves the controller data tracing and processing analysis capabilities, but the visualization and storage capabilities are limited and coupled together. The data were not closed-loop in the process design phase.

According to Fig. 2 and Table 2, it can be seen that accurate data tracking and intelligent process analysis using STEP-NC require getting through the data flow between CAD/CAM/CNC. However, commercial CAD/CAM information cannot generate STEP-NC files, and the cost of transforming existing commercial CNC machine tools will be too

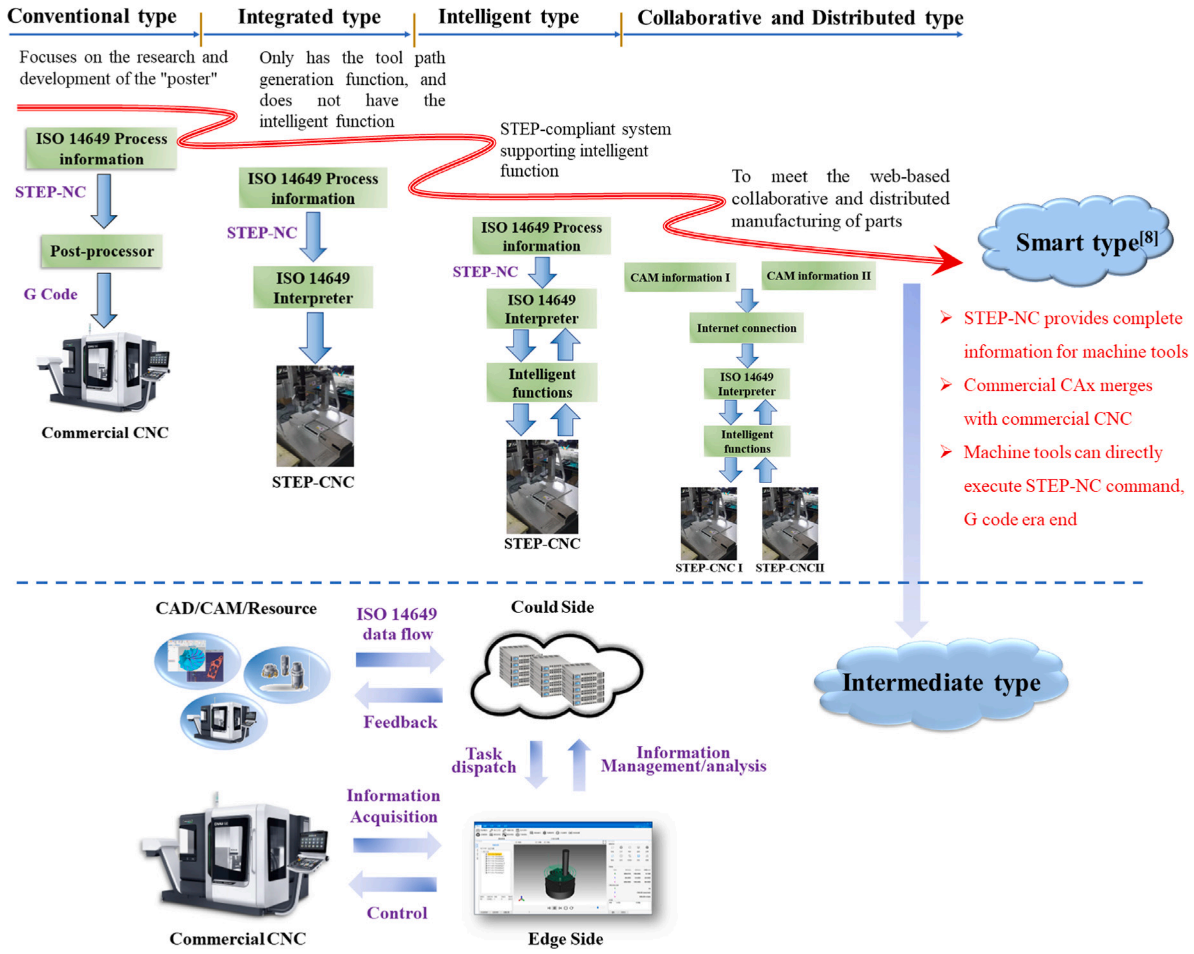


**Fig. 2.** Development of STEP-compliant manufacturing systems.

**Table 3**
Edge–cloud collaborative manufacturing system advantages.

| Manufacturing system | Data processing | Information interaction | Knowledge analysis |
|---|---|---|---|
| Traditional manufacturing | Redundancy<br>Unclear | Processing information through people<br>Unable to retrace Information | Limited knowledge |
| Edge–cloud collaboration manufacturing | Real-time data processing at the edge<br>Massive manufacturing data processing at the cloud | Distributed & collaborative information interaction<br>Information retraction | Knowledge model driven |

high for the manufacturing enterprises to accept. Therefore, this paper proposes an intermediate solution before implementing an 'intelligent' STEP-compliant system. The edge–cloud collaboration framework is used to assist STEP-NC in implementing accurate data tracking and intelligent process analysis.

### *2.2. Edge–cloud collaboration manufacturing system*

The most significant difference between edge–cloud collaborative manufacturing systems and other manufacturing systems is edge–cloud collaboration. Edge side system is deployed next to the CNC machine and uses lightweight algorithms to analyze real-time machining data. The cloud is arranged on the enterprise private cloud, using big data algorithms to process the huge amount of manufacturing data stored in the cloud database [33,34]. As shown in Table 3, the edge–cloud collaborative manufacturing system has obvious advantages in data processing, information interaction, and knowledge analysis compared with other manufacturing systems [35–37].

Edge–cloud collaboration is capable of establishing a connection between the physical world and the virtual world. The information about objects in the physical world is uploaded to cyberspace in the cloud through the edge system for processing, and then the processing results are fed back to the edge system to implement the control of the objects. As a result, the edge–cloud collaboration approach is widely used in many fields. Dimitrios et al. [38] highlighted the application value of edge–cloud collaboration, noting that edge–cloud systems can facilitate the digital transformation of the manufacturing industry. Chen et al. [39] deliberated on the efficient exchange of information, data fusion, and collaborative methodologies between the edge and cloud. They employed edge–cloud collaboration to achieve proactive maintenance of the production line. Afrin et al. [40] devised a robot framework for edge–cloud collaboration, exploring synchronous optimization problems aiming to minimize maximum completion time, energy consumption, and overall resource costs. Qi et al. [41] introduced an intelligent manufacturing hierarchical structure for digital twin workshops, leveraging edge computing, fog computing, and cloud computing. This framework presents vast prospects for advancing smart manufacturing. Lou et al. [42] verified the feasibility of the intelligent machine tool architecture based on an edge–cloud system. Sood and

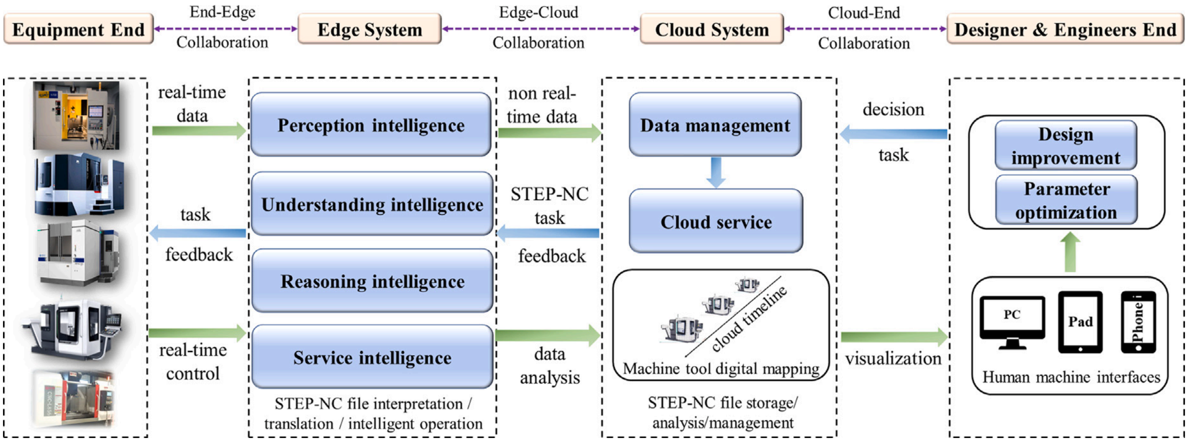


**Fig. 3.** Edge–cloud collaboration system architecture supporting STEP-NC.

Mahajan [43] used edge–cloud collaboration to assist the CPS system in achieving differentiation, detection, and prevention of mosquito-borne diseases. In terms of engineering applications, DJI drones are equipped with LorenzAL-Link modules that enable intelligent scenarios of edge–cloud collaboration [44]. It can be seen that edge–cloud collaboration can assist manufacturing systems in achieving efficient and intelligent upgrades.

### *2.3. Challenges of edge–cloud collaboration manufacturing supporting STEP-NC*

In summary, the STEP-NC is a desirable method that improves the reliability, production efficiency, and versatility of manufacturing data transmission and interaction, but the mainstream CNC systems currently used by manufacturing enterprises are not compatible with the STEP-NC and cannot be applied to traditional CNC machining. In addition, the adoption of the STEP-NC resulted in the explosive data growth of traditional CNC machining processes, posing challenges to STEP-NC solutions. Therefore, the edge–cloud synergy method deploys the edge system on the machine tool side as the intelligent agent of the CNC machine tool, which eliminates the issue of incompatibility between the STEP-NC and commercial CNC machine tools. The collaborative cloud can alleviate the explosive growth of manufacturing data utilization. The edge–cloud collaboration solution that supports STEP-NC can be used as an intermediate solution to implement the next-generation intelligent CNC system supporting STEP-NC.

## 3. Edge–cloud collaboration manufacturing supporting STEP-NC

In order to satisfy accurate data tracing and intelligent process analysis without modifying the machine tool, the authors proposed an intermediate solution. It allows manufacturing enterprises to implement the flow of complete processing information that supports STEP-NC and can trace and analyze the data associated with the process STEP from both time and space dimensions.

### *3.1. Edge–cloud collaboration manufacturing framework*

Fig. 3 shows the edge–cloud collaborative system framework that supports STEP-NC. Fig. 4 shows the functional architecture diagram of the system. The edge side system is arranged next to a commercial CNC machine to match its processing resources (static manufacturing data) and processing signal acquisition (dynamic manufacturing data). Data is collected through time-tag and workstep. The cloud stores STEP-NC files containing complete process information and manufacturing big data collected through various databases. The complete process information in STEP-NC implements information exchange and closed-loop by means of edge–cloud collaboration. The complex and multi-responsibility CNC machining process is broken down, and each person is only responsible for a part of the content.

#### *3.1.1. Edge side system*

Edge side system is deployed next to commercial CNC and acts as an intelligent agent. The commercial CNC machine tool analyzes the modeling, isolation hardware, automatic tool matching, tool parametric modeling, process data monitoring, processing step reasoning, online simulation, and all-element process information through the STEP-NC file of the edge side system. Management and other functions are able to accomplish Perception intelligence, understandable intelligence, reasoning intelligence, and Service intelligence.

(1) Perception intelligence: Perception intelligence refers to the perceptual ability of an index-controlled machine tool to CNC machining data. The current lack of perceptual intelligence of traditional commercial CNC machine tools leads to machining process information not being fully accessible, stored, and utilized. As an intelligent agent of traditional CNC machine tools, the edge side system enables the perception intelligence of CNC machine tools by isolating the CNC system hardware. Edge side system has a built-in communication interface protocol for different CNC systems, which implements the acquisition of real-time machining signals from different CNC machines. Edge side system has STEP-NC parsing and G code post-processing functions to retain complete process information and enable post-processing of G codes for heterogeneous CNC machines.

(2) Understanding intelligence: Since the G code programming standard only stores simple tool motion commands, the current CNC machine tools cannot intelligently understand the processing technology of parts. Using STEP-NC to replace G code as the carrier of information storage and transmission can help the current traditional commercial CNC machine tools to implement understanding intelligence. The edge side system can establish the corresponding process information model of CNC machining according to STEP-NC (including process information such as machine tools, cutting tools, work steps, processing strategies, etc.), and display process information according to the work steps in a tree-like hierarchy, which implements the understanding intelligence of traditional CNC machine tools.

(3) Reasoning intelligence: The perception intelligence and understanding intelligence implemented by the edge side system assisting the CNC system provide the data and model basis for the realization of reasoning intelligence. Reasoning intelligence refers to inferring the current machining state (including geometric state and physical state) of the current part based on the

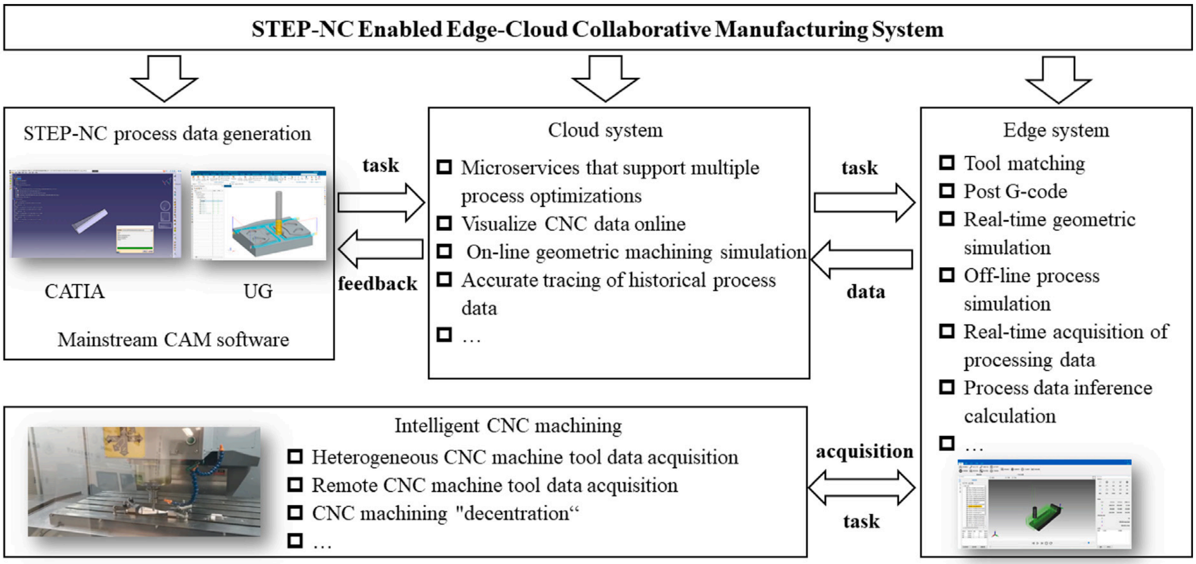


**Fig. 4.** Functional architecture diagram of the system.

process data collected from the actual machining of the part and the understood information model. Edge side system can display STEP-NC task files by machining step. CNC engineers can use the work steps to understand the machining information of the part and perform subsequent analysis. In addition, edge side system builds a virtual simulation environment within the system based on the complete process model to implement the joint geometric-physical online simulation of the part machining process.

(4) Service intelligence: The service intelligence of the edge side system enables the traditional CNC system to have the ability to make demands and serve demands. The edge side system is able to monitor and reason through all-factor process information and accurate parts processing status, and can automatically respond to decisions when facing the intelligent service requirements of actual factory processing. In addition, the virtual environment of the edge side system and the real processing run synchronously, and the decision results of the virtual environment can be fed back to the real CNC processing to improve the processing quality. Nevertheless, it is impossible to better implement service intelligence only by the edge, and it needs to work with the cloud side system to implement the mutual cooperation between various services.

### *3.1.2. Cloud side system*

Edge side system enhances the intelligence of CNC machining as an intelligent agent of traditional CNC machines, but the computing power limits the processing of manufacturing big data. The cloud side system, as a collaborator of the edge system, is a way to implement the distributed manufacturing of CNC machining. Cloud mirroring, data management, cloud services and other functions can also make up for the shortcomings of the edge side system and further enhance the intelligence of CNC machining of traditional CNC machine tools.

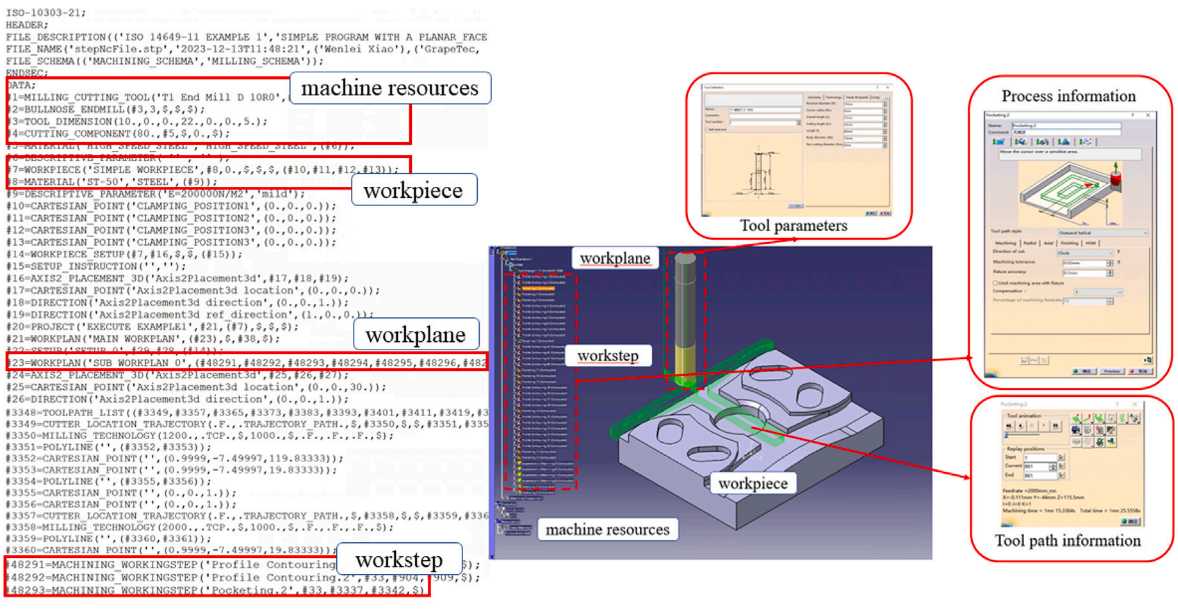
(1) Cloud mirror image: The cloud side system manages the 4D cloud mirror image of real CNC machine tools in the physical world and various physical models of CNC machining. Users can log in to the cloud system remotely according to their accounts and get information about the current CNC machine by querying the cloud mirror to connect to the specified edge side system. In addition, the edge side system handles the information of the current process of CNC machine tool, which is equivalent to the slice at this moment on the machine tool cloud mirror image timeline. Cloud system can store the historical data of CNC machining process into the machine tool cloud mirror, which enables workers to retrace the process information of CNC machine tools at different moments on the timeline through the cloud mirror.

(2) Data management: The data management function of the cloud side system needs to achieve the distribution of processing tasks and the storage of information. In terms of distribution of processing tasks, the cloud side system implements distributed manufacturing of traditional CNC machining while retaining all-factor process information of STEP-NC parts through automated processes. In terms of information storage, the cloud side system is equipped with a variety of databases. For example, the time series database is used to store the process data collected during the processing, and the object-oriented database is used to store and process the huge process data of STEP-NC.

(3) Cloud service: Building a service cluster in the cloud side and collaborating with the edge side system can better implement the service intelligence of traditional CNC machine tools. Cloud services can be expanded according to the needs of CNC machining. For example, it can implement the service of recommending cutting tools according to the CNC machining environment; the service of automatically dispatching STEP-NC task files according to the current CNC machine tool status; the service of remotely monitoring the online processing status of the current CNC machine tool; the processing feature-oriented process for parts processed by different CNC machine tools big data optimization and analysis services, etc. Any demand for CNC machining can be extended at the cloud side in the form of services to implement intelligent machining.

### *3.2. Process data acquisition and presentation*

The construction of the system needs to rely on the support of complete process data. In the case of not breaking the commercial CAD/CAM software design mode, simple, fast, and comprehensive export of the complete and unified format of the part process information is the primary requirement for realizing the information interaction of each link of the system.



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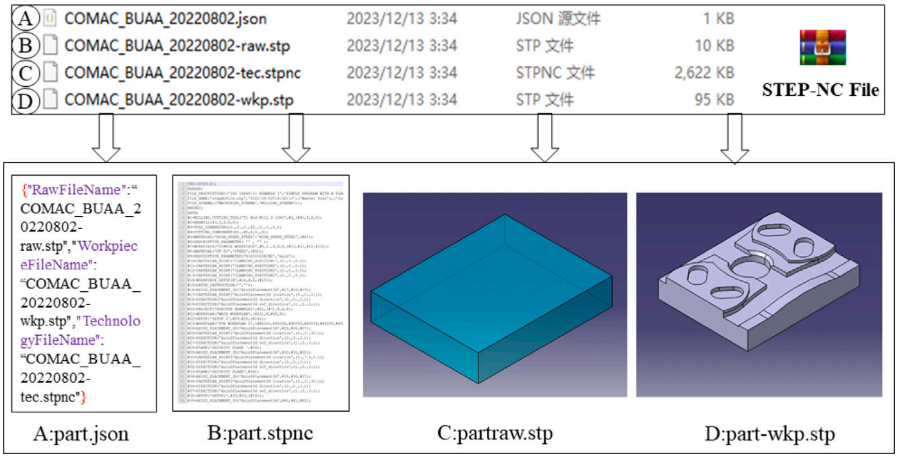
**STEP-NC File** **Part Process Design**

**Fig. 5.** CATIA can export the process information.



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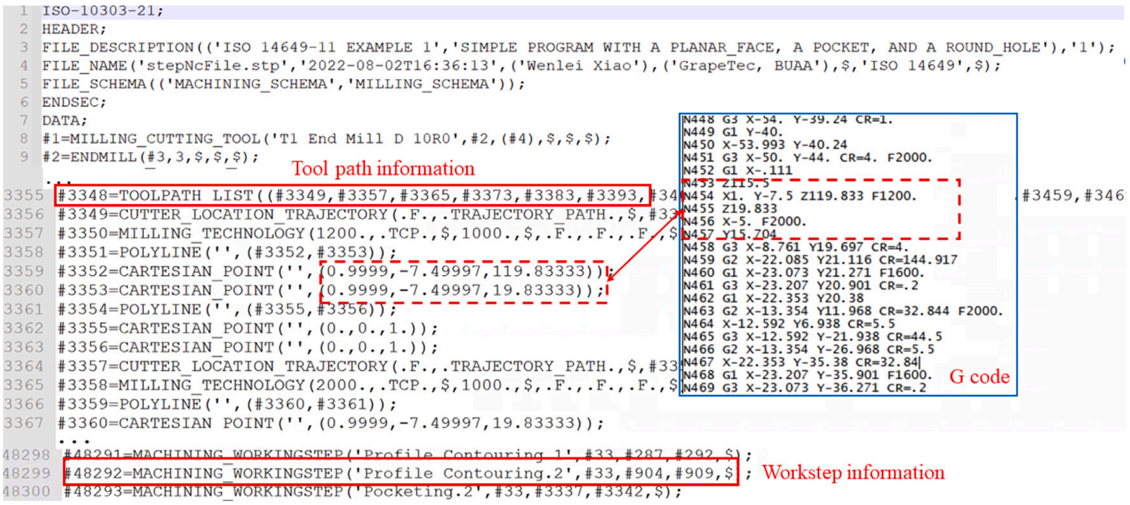
| B | COMAC_BUAA_20220802-raw.stp | 2023/12/13 3:34 | STP 文件 | 10 KB |
| C | COMAC_BUAA_20220802-tec.stpnc | 2023/12/13 3:34 | STPNC 文件 | 2,622 KB |
| D | COMAC_BUAA_20220802-wkp.stp | 2023/12/13 3:34 | STP 文件 | 95 KB |

**STEP-NC File**

```
{"RawFileName":“COMAC_BUAA_20220802-raw.stp","WorkpieceFileName":“COMAC_BUAA_20220802-wkp.stp","TechnologyFileName":“COMAC_BUAA_20220802-tec.stpnc"}
```

A:part.json B:part.stpnc C:partraw.stp D:part-wkp.stp

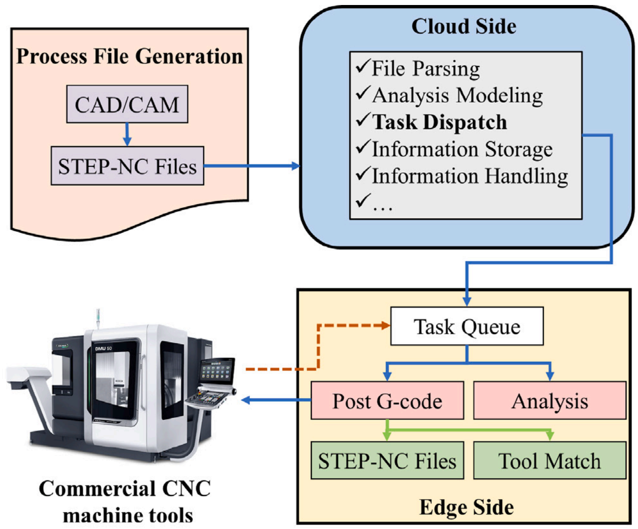
**Fig. 6.** Exported STEP-NC zip file.



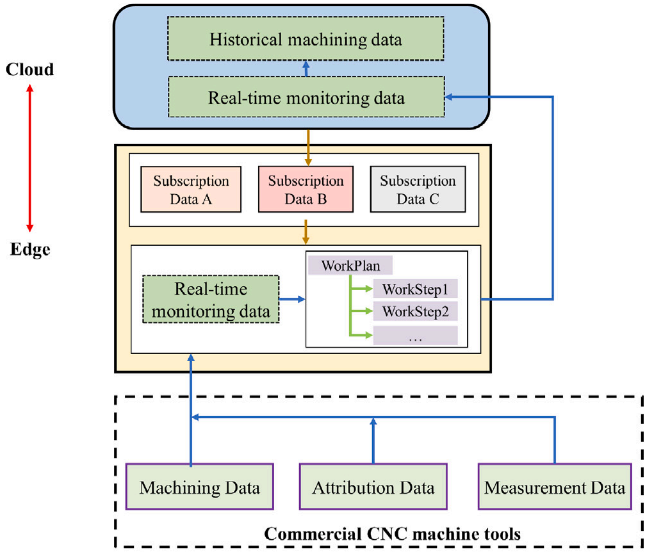
```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION(('ISO 14649-11 EXAMPLE 1','SIMPLE PROGRAM WITH A PLANAR_FACE, A POCKET, AND A ROUND_HOLE'),'1');
FILE_NAME('stepNcFile.stp','2022-08-02T16:36:13',('Wenlei Xiao'),('GrapeTec, BUAA'),$,'ISO 14649',$);
FILE_SCHEMA(('MACHINING_SCHEMA','MILLING_SCHEMA'));
ENDSEC;
DATA;
#1=MILLING_CUTTING_TOOL('T1 End Mill D 10R0',#2,(#4),$,$,$);
#2=ENDMILL(#3,3,$,$,$);
...
#3348=TOOLPATH LIST((#3349,#3357,#3365,#3373,#3383,#3393,#34                  #3459,#346
#3349=CUTTER_LOCATION_TRAJECTORY(.F.,.TRAJECTORY_PATH.,$,#33
#3350=MILLING_TECHNOLOGY(1200.,.TCP.,$,1000.,$,.F.,.F.,.F.,$
#3351=POLYLINE('',(#3352,#3353));
#3352=CARTESIAN_POINT('',(0.9999,-7.49997,119.83333));
#3353=CARTESIAN_POINT('',(0.9999,-7.49997,19.83333));
#3354=POLYLINE('',(#3355,#3356));
#3355=CARTESIAN_POINT('',(0.,0.,1.));
#3356=CARTESIAN_POINT('',(0.,0.,1.));
#3357=CUTTER_LOCATION_TRAJECTORY(.F.,.TRAJECTORY_PATH.,$,#33
#3358=MILLING_TECHNOLOGY(2000.,.TCP.,$,1000.,$,.F.,.F.,.F.,$
#3359=POLYLINE('',(#3360,#3361));
#3360=CARTESIAN POINT('',(0.9999,-7.49997,19.83333));
...
#48291=MACHINING_WORKINGSTEP('Profile Contouring 1',#33,#287,#292,$);
#48292=MACHINING_WORKINGSTEP('Profile Contouring.2',#33,#904,#909,$);
#48293=MACHINING_WORKINGSTEP('Pocketing.2',#33,#3337,#3342,$);
```

```
N448 G3 X-54. Y-39.24 CR=1.
N449 G1 Y-40.
N450 X-53.993 Y-40.24
N451 G3 X-50. Y-44. CR=4. F2000.
N452 G1 X-.111
N453 Z115.5
N454 X1. Y-7.5 Z119.833 F1200.
N455 Z19.833
N456 X-5. F2000.
N457 Y15.704
N458 G3 X-8.761 Y19.697 CR=4.
N459 G2 X-22.085 Y21.116 CR=144.917
N460 G1 X-23.073 Y21.271 F1600.
N461 G3 X-23.207 Y20.901 CR=.2
N462 G1 X-22.353 Y20.38
N463 G2 X-13.354 Y11.968 CR=32.844 F2000.
N464 X-12.592 Y6.938 CR=5.5
N465 G3 X-12.592 Y-21.938 CR=44.5
N466 G2 X-13.354 Y-26.968 CR=5.5
N467 X-22.353 Y-35.38 CR=32.84
N468 G1 X-23.207 Y-35.901 F1600.
N469 G3 X-23.073 Y-36.271 CR=.2
```

**Fig. 7.** Generated STEP-NC file.



(a) STEP-NC compliant machining tasks



(b) Principle of dynamic data subscription and monitoring

**Fig. 8.** Closed loop of process data flow of the system.

### 3.2.1. *Export process data*

At present, there are very few commercial CAD/CAM software that can export STEP-NC information files in a unified format [12,45,46], so in order to ensure the information interaction of each link of the system, this paper takes CATIA as an example to introduce the method of exporting the STEP-NC file. The geometric information is described by manufacturing features, which include a variety of features involved in CNC machining, such as plane, slot, hole, etc. [47]. The geometry and process information are linked by the work steps, which is the basic unit of the STEP-NC program. It plans a fixed process for characteristic machining, each work step only allows the use of one tool and the same set of process parameters, and the specific sequence of work steps constitutes the solution of the part. This also shows that accurate traceability of manufacturing information in the form of work steps will bring benefits to the process design and optimization of parts.

The export of the STEP-NC file is shown in Fig. 5. CATIA's secondary development platform includes Automation API (Application Programming Interface), Knowledge Ware, Interactive User Defined Feature, and CAA (Component Application Architecture) four secondary development methods [48]. This article uses CAA (V5, C++) as the main programming method because it has the best integration, functionality, and efficiency performance. The exported STEP-NC file contains four parts: the retrieval file, the STEP-NC information file of the part, the geometry information of the part, and the blank geometry information of the part. As shown in Fig. 6, the feature definition and process planning method for generating STEP-NC information files corresponding to part information in CATIA were introduced by the research group in an article published in 2014 [12]. The previous work could not successfully derive STEP-NC information for the machining of parts with complex features. The current optimization method can implement the export of process information for all parts and has been applied in the process design end of COMAC. The generated STEP-NC file is shown in Fig. 7.

### 3.2.2. *Parsing STEP-NC files in the cloud*

In order to facilitate the delivery of part tasks by the process personnel, plug-ins have been developed within CATIA. Process personnel can export STEP-NC files containing complete process information with one-click through the plug-in and upload them to the cloud.

After uploading the file, the cloud will automatically start the service of parsing the STEP-NC compressed package file in the background:

(1) According to .json Search inside zip files: as shown in Fig. 6A, the .json file in the STEP-NC compressed package includes three categories: RawFileName, WorkpieceFileName, and TechnologyFileName, which correspond to the other three files in the compressed package.

(2) .stpnc file phasing: Fig. 6B .stpnc file contains the complete process information of parts processing, and there have been many studies on the parse of STEP-NC file [28], which are not described in detail here. After parsing the STEP-NC file information, it is automatically filled into the database for personnel to trace the historical information. In addition, the process designer can view the manufacturing data of each machining STEP of the part through the cloud, understand what happened in the machining step, and accurately trace the data.

(3) Application of .stp geometry information: Fig. 6C partraw.stp and Fig. 6D part-wkp.stp files are converted into .obj or .stl format in the cloud to provide geometric information to the cloud simulation service. The cloud simulation adopts three.js technology, and only pure geometric information is needed to achieve commonality, rendering effect, and simulation efficiency of the simulation. Therefore, cloud simulation services store geometry information in .obj or .stl format.

## 3.3. *STEP-NC compliant machining tasks*

The process designer can send the STEP-NC part processing task file to the machine edge system through the task distribution service of the cloud system. After receiving the task distribution service, the cloud will automatically reassemble the contents of the compressed package in Fig. 6 to meet the processing requirements of the current machine. As shown in Fig. 8, The edge system stores different processing tasks dispatched by the cloud into the task queue, selects the processing tasks according to the current working status of the CNC machine tool, and performs subsequent processing. G codes are automatically distributed to the CNC machine control system through Distributed Numerical Control (DNC) technology. The engineer simply clicks on the start machining command of the CNC to start machining the part. Additions and deletions for CNC machining tasks are dynamically synchronized to the edge system.

The system enables dynamic post G codes during the assignment of machining tasks. Different commercial CNC systems adopt different G code instructions, which leads to the need to manually modify the G code instructions according to the manufacturing resources on site before the manufacturing tasks are sent to the CNC system. The tool is a vital machine tool resource that affects the dynamic generation of

**Table 4**
Comparison of data acquisition interface performance of mainstream CNC systems.

| CNC model | Agreement | Subscription | Asynchronous read | Limit period (ms) | Batch read | Encoding | Data number |
|---|---|---|---|---|---|---|---|
| 840D-SL | OPC-UA | Support | Support | 50–150 | Support | Binary/XML | 600–1200 |
| 828D | OPC-UA | Support | Support | 50–150 | Support | Binary/XML | 600–1200 |
| 840D-PL | OPC-DA | Support | Support | 100–150 | Support | Binary | 600–1200 |
| FANUC | FOCAS | Nonsupport | Nonsupport | 100–200 | Nonsupport | Binary | 100–200 |
| TwinCAT | Ads/OPC | Nonsupport | Support | 100–200 | Support | Binary | User-defined |
| HNC-8 | HncApi | Nonsupport | Nonsupport | 100–200 | Nonsupport | Binary | 70–120 |
| GSK988T | GSKRM | Nonsupport | Nonsupport | 100–200 | Nonsupport | Binary | 100–150 |

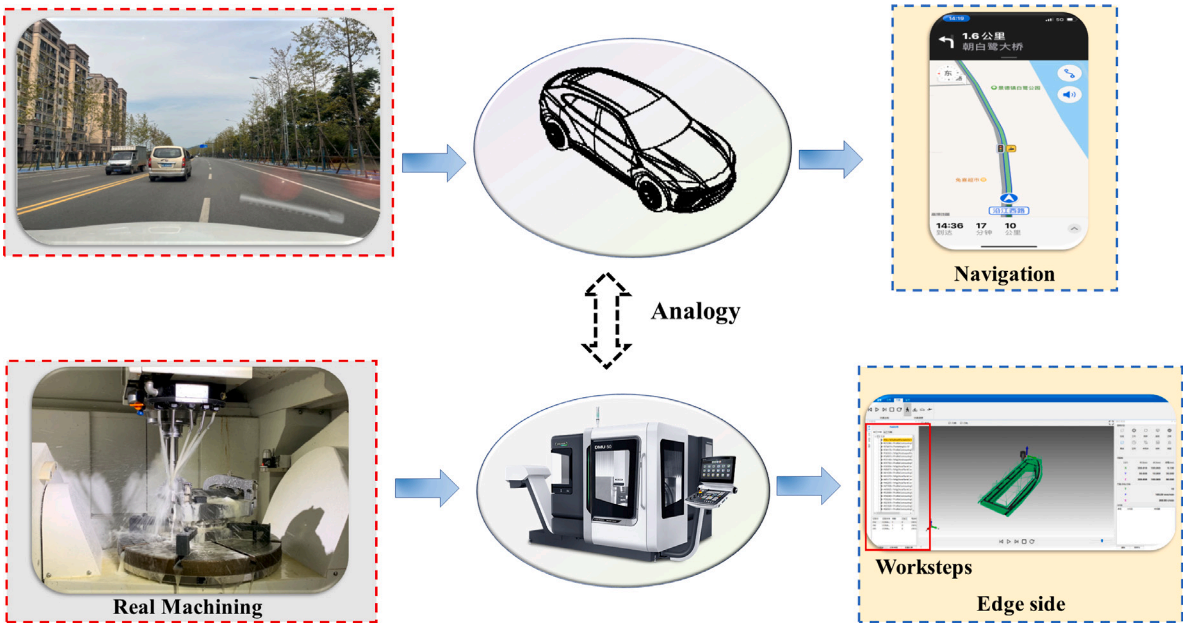


**Fig. 9.** Dynamic navigation-style tracing of on-site machining data.

G code. In real processing, (1) because the replacement of the worn tool may change the tool number of the tool in the tool library, it is necessary to manually modify the G code. (2) Due to the machining task of different batches of parts inserted into the CNC machine tool, the tool number in the G code is not the same as the tool number in the tool library, resulting in the need to manually modify the G code.

The edge side system is placed next to each commercial CNC machine and has a G code post-processor built in to match the CNC system. The cloud will send the manufacturing task to the edge, and the difference in machine processing instructions will be resolved by the rim. The edge side system can implement the dynamic matching of the tool number by establishing the resource model of the NC machine tool itself and the description of the tool in the STEP-NC process file. Combined with the extracted information such as tool track and process parameters in the STEP-NC file, the G code is posted.

### 3.4. In-situ dynamic data traceability

Information acquisition stands as the cornerstone for achieving precise data tracing, typically classified into direct and external hardware acquisition. The expeditious and comprehensive flow of processing information can be actualized through the aggregation of communication interfaces. The edge system, leveraging built-in communication protocols and unique variable identifiers (IDs) within the CNC system, facilitates data acquisition across diverse commercial CNC systems. Notably, certain existing commercial CNC machine tools like Siemens 840D powerline, Siemens 840D sl, and Siemens 828D offer information subscriptions accessible to a sole user for data collection. However, most commercial CNC machine tools lack support for data subscription, including the FANUC series, TwinCAT CNC, and Huazhong CNC Type 8. Consequently, disparate process personnel are compelled to invest substantial effort in manually selecting available data from the vast pool of manufacturing data gathered. The interoperability among heterogeneous CNC systems and the support process data tracing emerge as pivotal factors influencing software process data acquisition and analysis.

The performance analysis of the communication interface of heterogeneous CNC systems is of great significance to improve the operating efficiency of manufacturing systems. On the one hand, improper data acquisition will seriously affect the normal work of the CNC system, leading to the breakdown of CNC system service software. On the other hand, interface performance analysis can give full play to the advantages of various collection protocols and improve their operating efficiency. As shown in Table 4, this paper studies and compares the communication interfaces of mainstream CNC system models at home and abroad.

The efficiency of heterogeneous numerical control system acquisition is the key to data acquisition. According to the communication efficiency, the priority is set in three ways: synchronous read, asynchronous read, and subscription read. The priority of subscription is the highest, followed by asynchronous read and synchronous read has the lowest priority

In summary, as the agent of the CNC machine tool, the edge side system cannot implement the display of remote information and the processing of huge processing data. Therefore, the method of edge–cloud collaboration is adopted to solve the defects of edge systems through cloud image (information model of CNC machine tool built on cloud system). On the one hand, the cloud system can store the huge processing data collected at the edge. On the other hand, the edge side system processes the process data of the current processing

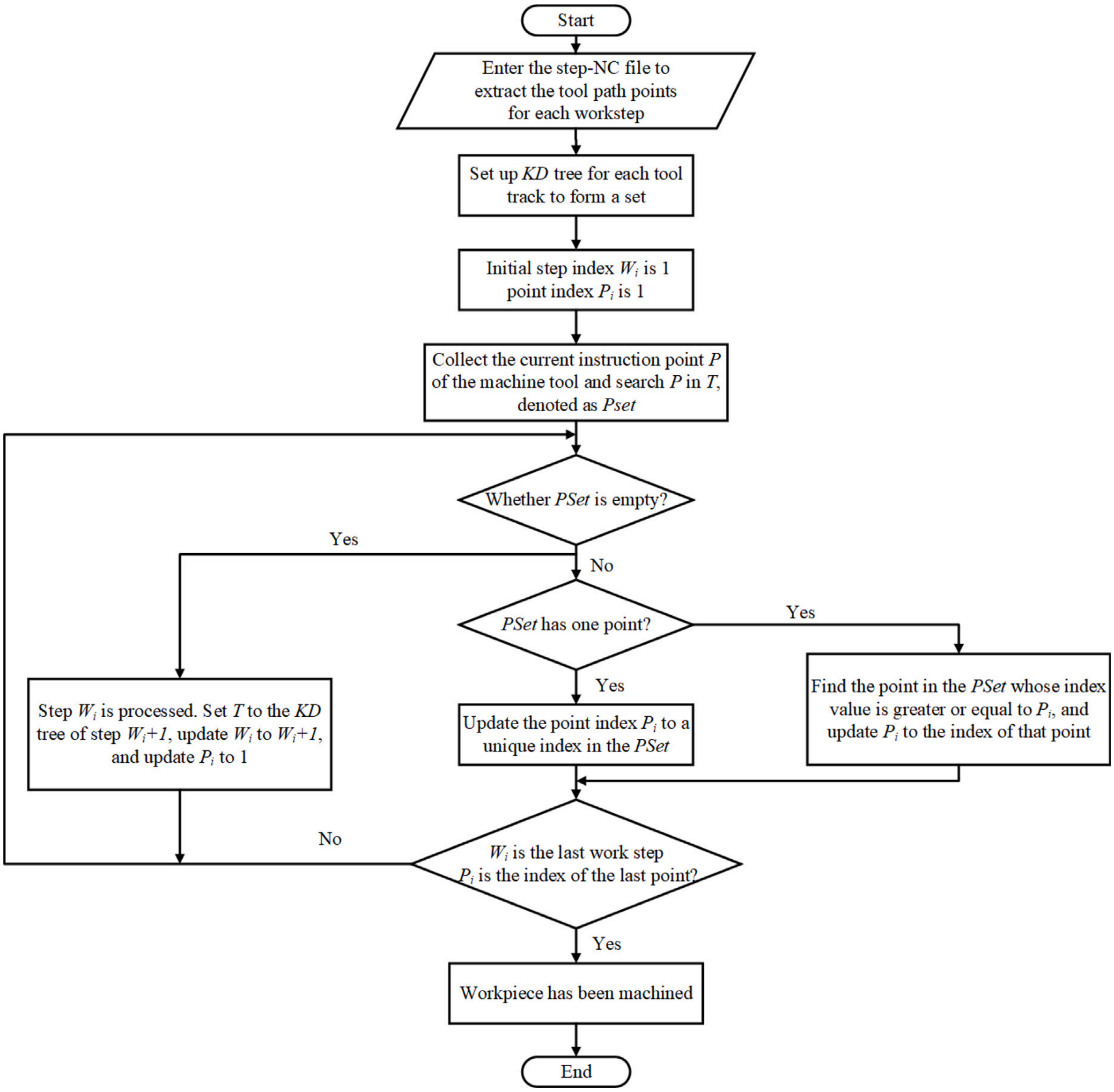


**Fig. 10.** Workstep matching algorithm flowchart.

process of the CNC machine tool, which is equivalent to the slice of the moment in the cloud image timeline of the machine tool. Users can freely and dynamically view manufacturing data according to the timeline. The cloud system allows users to log in remotely according to their accounts, and implement remote access to parts processing information. As shown in Fig. 8, different people have different requirements for accessing information. Faced with the need for different process information, remote personnel can use the mobile terminal to trace the interested process data through the cloud system, and edge personnel can trace the process data through the edge side system. The cloud system will store the process data of the parts processed by the current CNC machine tool, allowing the processing of each step of the part processing to be viewed through the cloud. Based on the collaboration of STEP-NC and edge–cloud, the closed-loop interaction of parts from the design of craftworkers to the manufacturing data collected by commercial CNC machine tools is implemented.

### 3.5. Data segmentation method based on worksteps

Since the commands in G code are continuous, they cannot be distinguished according to the working steps. Therefore, the synchronization of worksteps holds the following crucial significance for manufacturing systems:

(1) Real-time state data of NC machining process can be associated with specific machining operations. High-dimensional labeled data makes the machining process data orderly and structured. The data of each work step is recorded separately.

(2) Each step is uniquely corresponding to a tool and a tool path, which provides the basis for real-time geometric simulation.

The edge system can implement the real-time geometric simulation of the part machining process according to the step and the collected information. Visual modeling, including 3D models of tools, tool paths, and workpieces, is required foremost for the real-time geometric simulation of the associated steps in the edge system. The tool model is built by extracting the parameters of tool type and tool size from the STEP-NC file. The tool path model needs to be constructed according to the steps obtaining a list of tool path models ordered by steps, and only the currently executing tool path is displayed in the simulation environment during the machining process. The workpiece model can be exported as an STEP (AP203) file by the design system and then input into the simulation system for display. In addition to the visual modeling, real-time motion simulation of the tool is also needed. The

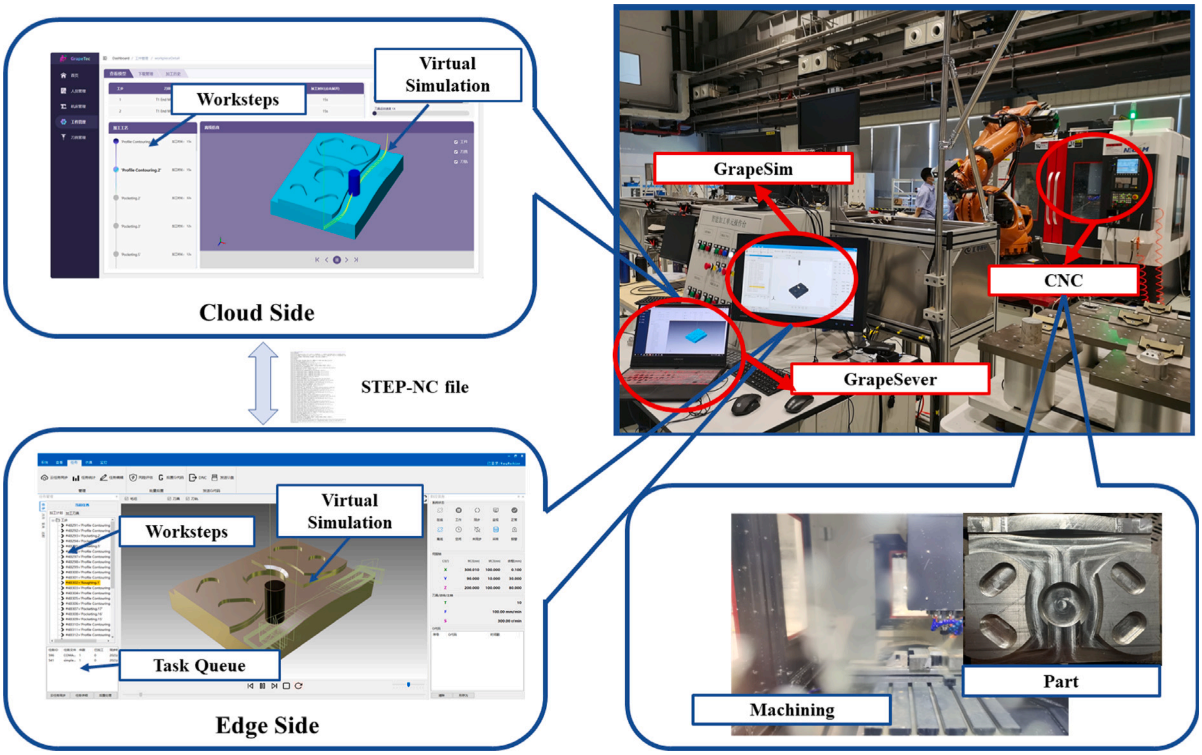


**Fig. 11.** Edge–cloud collaboration manufacturing supporting STEP-NC.

authors [49] have proposed a STEP-NC-oriented machining simulation method in 2020, which can ensure the accuracy and efficiency of the simulation in the real machining process.

(3) Process information of each working step is accurately traced, which provides the basis for the technologists to accurately optimize the process and analyze the tools. Due to the constraints of the edge system, the data associated with the steps will be visible in the cloud system.

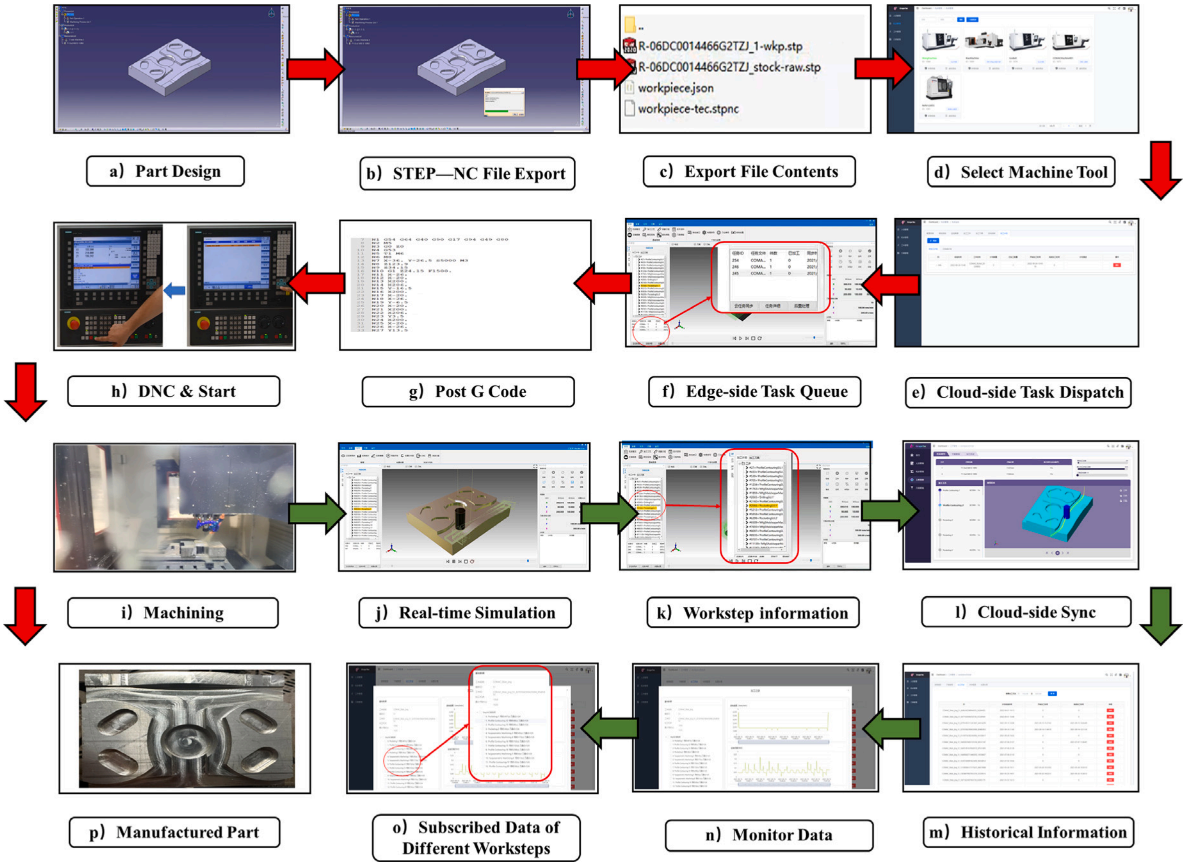
The tool path information is contained in the STEP-NC information stored in the edge, which provides a complete tool path "map" prior to the machining. When the part is just processed, the edge does not know what the specific step the tool machining is. In machining process, the current step of the tool can be calculated by comparing the real-time collected position data of tool position point with the tool path data in STEP-NC. Since the machine tool is machining sequentially according to the G code, as the incipient step is determined, the subsequent step can be divided according to the 'map'. As shown in Fig. 9, which is the same concept as navigation.

The tool path points of STEP-NC and G code are compared with each other in Fig. 7. Each workstep in STEP-NC is completed by a section of tool path, and each tool position point has a one-to-one correspondence with G code. The proposed working step synchronization algorithm is to search the position of the actual tool command position point in the theoretical tool path point of workpiece machining, locate the working step described by the tool path section where the tool is currently located, and then determine the currently machining workstep.

In the algorithm, *Wi* and *Pi* are used to indicate that the current machining process has reached the *Pi* instruction point of the *Wi* workstep. During the machining process, the feed axis instruction position *P* is periodically collected and the position of *P* is searched in the STEP-NC point set for updating *Wi* and *Pi*. The machine tool instruction point refers to the instruction end point reached by the designated axis in the NC code, for example, the instruction point in the instruction G01 X1Y2Z3 is Point (1,2,3). *KD* tree algorithm is applied in the step synchronization algorithm for fast point search, making the time complexity of the search reaching *log n*. Fig. 10 shows the simplified flow of the synchronization algorithm, and the specific steps are described as follows:

(1) Input the STEP-NC file to extract the set of tool path points for each step;
(2) Construct a *KD* tree for the tool path points of each step, and then obtain a set of *KD* trees;
(3) Set three variables to complete the initialization work. Set both the index value of current step *Wi* and point *Pi* to 1, and initialize the *KD* tree *T* of current step as the first one of the *KD* tree set.
(4) Collect the current instruction point *P* of the machine tool and search it in tree *T*. The result returned is the point set *PSet* in the tree *T* that coincides with the 3D coordinates of point *P*, moreover, each point in *PSet* has an index value, which is used to represent the place of the point in the tool path point set of step *Wi*.
(5) The results of *PSet* may have three cases:
    (a) The *PSet* is empty, point *P* cannot be found in step *Wi*, indicating that step *Wi* has been completed and need to update *Wi*, *Pi* and *T* to *Wi* + 1, 1 and the corresponding *KD* tree of step *Wi* + 1.
    (b) There is only one point in the *PSet*, which indicates that step *Wi* is still under machining. This way, it is only necessary to update *Pi* to the index value of the only point in *PSet*.
    (c) There are more than one point in the *PSet*, which also means step *Wi* is still under machining, but the Position of point *P* is passed through more than once in the step *Wi*. At this time, the point in the *PSet* whose index value is just greater than or equal to *Pi* corresponds to the point *P*, so the *Pi* is updated to the index value of this point.

For case (b) and (c), after updating the index value *Pi*, it may be the last command tool path point of the last step, which indicates that all steps have been completed.



..
R-06DC0014466G2TZJ_1-wkp.stp
R-06DC0014466G2TZJ_stock-raw.stp
workpiece.json
workpiece-tec.stpnc

**Fig. 12.** Support STEP-NC edge–cloud collaboration system.

**Machining record**

**Base data**

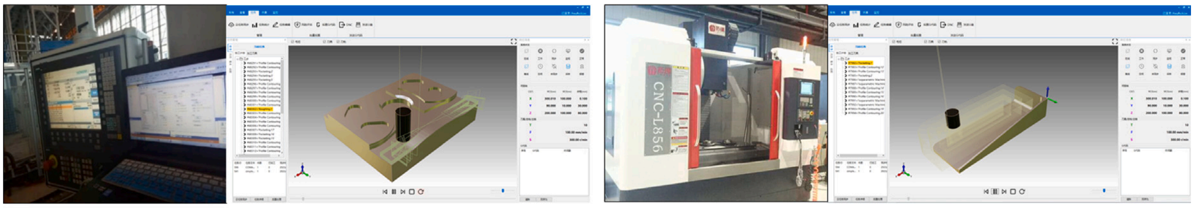
**Name** COMAC_BUAA_20220802

**ID** 79

COMAC_BUAA_20220802_7

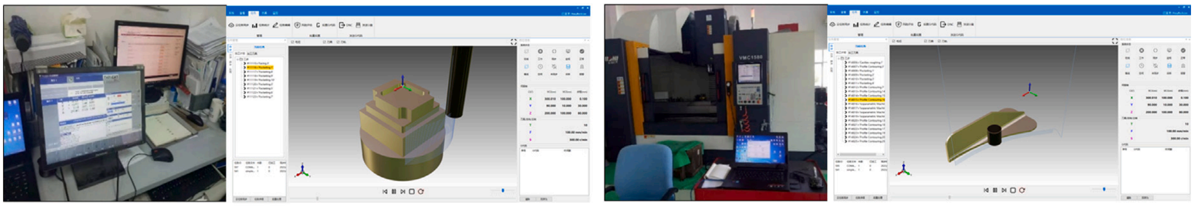
☐ 20. 'Profile Contouring.38' 用时:49(s) 刀具I...
☐ 21. 'Profile Contouring.37' 用时:88(s) 刀具I...
☑ 22. 'Profile Contouring.36' 用时:46(s) 刀具I...
☐ 23. 'Pocketing.14' 用时:30(s) 刀具ID:155
☐ 24. 'Profile Contouring.35' 用时:83(s) 刀具I...

**Fig. 13.** Collected signal of a certain workstep of the part.



840Dsl

828D



TwinCAT CNC

Huazhong CNC

**Fig. 14.** Heterogeneous numerical control system data acquisition.

(6) If the workpiece is still not completed, the algorithm returns to step (4) until all steps are finished. The G code instruction of CNC machine tool is used to assist positioning.

## 4. Case study

The authors propose a prototype of an edge–cloud collaboration system based on the above framework to support the STEP-NC and select the processing of parts of a large passenger aircraft in COMAC's intelligent manufacturing project as a case study of the research team.

According to the proposed system framework, the design team divided the whole system into process information export, cloud, edge, and CNC machine tool. As shown in Fig. 11, the laboratory developed the edge side system GrapeSim on the PC side through self-developed GPCORE, which was deployed next to commercial CNC machine tools. GrapeServer, a cloud system developed through cloud technology, can be deployed in a factory private cloud. The edge side system and the CNC machine tool establish communication through network cables, and the cloud system establishes communication through the Internet.

Fig. 12 shows the use of this system to implement the intelligent processing of parts of a large passenger aircraft. In Fig. 12, (a) to (h) represent the data flow for task deployment, where (c) to (g) illustrate task processing both at the cloud and edge sides, and (g) to (h) depict the issuance of component machining tasks. On the other hand, (i) to (o) represent the data flow for component machining information collection, where (i) to (j) illustrate the collection of machining information, and (j) to (o) represent simulation, analysis, and storage of machining data at both the edge and cloud sides. Finally, (p) denotes qualified components. Thus, this case exemplifies the system's closed-loop nature and bidirectional data flow. Among them, the commercial machine tool adopts the Shanghai Nuozhuoli CNC machine tool, and the CNC system uses the Siemens 840D sl. The edge–cloud collaboration system allows designers to still use the familiar commercial CAM software. The passenger aircraft part completes the process design through the CATIA Process. After designing the part processing process, the technician can export the STEP-NC file with a single click and upload it to the cloud system GrapeServer, as well as selecting the digital twin model of the corresponding machine tool in GrapeServer. Its detailed information contains all the information of the machine tool, including configuration, CNC system, monitoring data, machining workpiece, machining tool, machining plan, etc. Through the processing plant, the processing task of the part can be sent to the edge side system GrapeSim, and the planned deletion operation can also be carried out through the processing plant. GrapeServer tasks are stored in GrapeSim in the form of a queue. When a craftsman deletes a machining plan through GrapeServer, GrapeSim will synchronize the corresponding tasks through the cloud task synchronization function. Since GrapeSim contains the twin model of the CNC machine tool, it matches the tool number of the STEP-NC file in the task according to the tool model information of the CNC machine tool before the processing task is issued. After matching the tool number, GrapSim will install the corresponding G code processing program based on the CNC system model. Then it is sent to the CNC system through DNC to start machining.

The large passenger aircraft parts are processed by Siemens 840Dsl numerical control system. GrapeSim obtains various machine signals in the numerical control system through the OPC UA communication protocol. The collected manufacturing signal is automatically associated with the processing workstep through the STEP-NC "map". As shown in Fig. 11, the processing situation of each work step can be monitored in real-time through GrapeSim geometric simulation, and the processing situation of each work step can also be viewed through GrapeSever geometric simulation. In addition, as shown in Fig. 13, process personnel can view machining data for each step of the part in GrapeSever in the cloud. At the same time, real processing data collected in real-time is also stored by GrapeSever in the cloud for historical viewing. The machining personnel can follow the manufacturing machining information of the part according to workstep-tag through the edge. Remote personnel can follow the manufacturing data of the part according to workstep-tag through the cloud.

Based on this, the manufacturing data form a closed loop from the technician part design to the commercial machine tool processing, and then from the commercial machine tool processing to the guide to the technician part design. The process personnel can achieve accurate data tracking and intelligent information analysis for the machining of parts through the system. It lays a foundation for manufacturing enterprises to implement intelligence.

## 5. Discussion

Considering the challenge of intelligent manufacturing processes that support full-element process information in current manufacturing enterprises, an edge–cloud collaborative system supporting the STEP-NC is proposed in this paper. In order to further verify the applicability of the system, several case processing tests were carried out on several machine tools of COMAC. As shown in Fig. 14.

It can be seen from Fig. 14 that the current edge–cloud collaborative system supporting STEP-NC can be well-compatible with the heterogeneous CNC systems of manufacturing enterprises, and the system has good applicability for simple and complex parts. In addition, the system has the following advantages:

- Firstly, for the conflict between commercial CNC machine hardware and STEP-NC execution system, the proposed edge–cloud collaboration method achieves the communication between heterogeneous CNC machine hardware and STEP-NC execution system under the precursor of ensuring that manufacturing companies do not modify the current commercial CNC system. In addition, the method is an intermediate solution for current manufacturing companies to achieve smart manufacturing. In the future, STEP-NCenabled edge side systems can be integrated with CNC systems, offering the possibility to achieve manufacturing process intelligence.

- Secondly, the edge–cloud collaborative system supporting the STEP-NC can perform offline or real-time geometric simulation of parts according to work steps at the edge side system. At the same time, the method of STEP-NC "navigation" is used to associate the collected data with the workstep of the part, and the process personnel can view the processing data of each work step of the part in GrapeSever. The system implements machining data processing with workstep-tag.

- Finally, the edge–cloud collaboration system that supports the STEP-NC proposed by the author makes it possible for manufacturing enterprises to have a two-way flow of manufacturing data under the traditional NC machining mode. The dynamic data and static data of massive manufacturing data can be processed cooperatively through this system, and more favorable knowledge can be extracted for processing. Thus, it improves the intellectualization of traditional NC machining.

Although the authors' research team has successfully applied the proposed system to an aircraft part manufacturing case in a manufacturing company, several suggestions can be extended for future research in the machining system.

- To cope with the changing processing environment and increasingly complex market demand, manufacturing companies are requesting intelligence upgrades to achieve cost reduction and efficiency while meeting the stringent quality requirements of the parts. The intelligence upgrades require manufacturing systems that can autonomously adapt to the complex and changing manufacturing environment to complete the processing of parts. When machine tools encounter requirements like tool selection, tool life prediction, and process optimization, they can autonomously solicit relevant services from the system to meet these demands. The system proposed in this paper has only partially implemented the deployment of services in its cloud, and more in-depth research is needed in the future for multiple service technologies in the manufacturing process to form a microservice cluster with multiple services supporting each other.

- In addition to the establishment of cloud service clusters, future work should also focus on the research of algorithms for processing dynamic data in the edge based on changes in the environment. The CNC machining environment of parts is complex and changeable, and more dynamic data need to be processed by intelligent edge side system to assist the machine tool, which still requires a lot of effort.

- Although the diversity of commercial CNC systems plays an important role in global manufacturing companies, they are also considered a key factor in hindering the intelligent upgrade of current manufacturing companies. In China, it is relatively common for manufacturing companies to have multiple different brands of CNC systems within them and to build a production line because of the machining of a single part. The resources of the machine tool are not reused by the processing of other parts. Closed commercial CNC systems greatly reduce the intelligence of part manufacturing. The manufacturing system proposed in this paper can assist manufacturing companies in achieving increased intelligence, but it is only an intermediate solution to achieve intelligent manufacturing of parts. Therefore, proposing a new system to help manufacturing companies achieve intelligence still requires a lot of effort.

## 6. Conclusion

Aiming at the challenge of improving the intelligence of parts processing in manufacturing enterprises, an edge–cloud collaborative system supporting the STEP-NC is proposed in this paper. The main contribution of this work lies in the following two levels. From the perspective of information interaction and data flow, the system establishes a two-way data flow based on STEP-NC to implement dynamic task delivery and data subscription according to the machining environment. From the point of view of data traceability, the system uses the workstep-tag to process the real machining data. The workstep based online machining process simulation and data segmentation are implemented to make the traceability of manufacturing data more accurate. The prototype system has been installed in the actual workshop of COMAC, and experiments are carried out on the CNC machine tool of COMAC parts manufacturing, which verifies the feasibility of the proposed method.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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