An Approach for Enabling Intelligent Edge Gateway Based on Microservice Architecture in Cloud Manufacturing

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(Received 30 September 2021; revised 10 March 2022; accepted 20 June 2022)

Abstract: Cloud manufacturing has become a reality. It requires sensing and capturing heterogeneous manufacturing resources and extensive data analysis through the industrial internet. However, the cloud computing and service-oriented architecture are slightly inadequate in dynamic manufacturing resource management. This paper integrates the technology of edge computing and microservice and develops an intelligent edge gateway for internet of thing (IoT)-based manufacturing. Distributed manufacturing resources can be accessed through the edge gateway, and cloud-edge collaboration can be realized. The intelligent edge gateway provides a solution for complex resource ubiquitous perception in current manufacturing scenarios. Finally, a prototype system is developed to verify the effectiveness of the intelligent edge gateway.

Key words: edge computing; intelligent gateway; microservice architecture; cloud manufacturing

CLC number: TP29 **Document code:** A **Article ID:** 1005-1120(2022)03-0338-11

0 Introduction

With the integration of manufacturing technology, information technology, and network technology, the manufacturing industry faces a revolution in dynamic resource management. The new scenarios require manufacturing companies react rapidly to meet market and consumer needs. In the novel networked hybrid manufacturing, the underlying entity is the execution unit of the manufacturing system and has been dramatically increased. These manufacturing resources complete networked tasks by sharing processing capabilities.

As a new service-oriented networked manufacturing paradigm, cloud manufacturing has promoted the continuous development of the manufacturing industry towards intelligence and service. By contrast, the traditional manufacturing system is divided into equipment, control, workshop, enterprise, and collaboration layers according to physical attributes[1]. It is precise that the multi-layer structure has become increasingly flat during the industrial internet of thing (IIoT) development. At the same time, discrete manufacturing resources can be accessed to the cloud manufacturing platform through the network[2].

Manufacturing resource perception and access is an essential part of cloud manufacturing. In this context, the comprehensive perception and access to various manufacturing resources is the primary support for networking and servicing. Therefore, the original multi-layer architecture divided according to physical attributes can be simplified into three layers according to its functions: The physical infrastructure layer, control layer, and application layer[3-4]. As an aggregation of all manufacturing resource entities, the physical infrastructure layer provides the hardware foundation for cloud manufacturing. The control layer links manufacturing resources and manufacturing services. Finally, the application

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How to cite this article: WANG Liping, TANG Dunbing, NIE Qingwei, et al. An approach for enabling intelligent edge gateway based on microservice architecture in cloud manufacturing[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2022, 39(3): 338-348.

http://dx.doi.org/10.16356/j.1005-1120.2022.03.008

layer provides the scheduling optimization between consumer needs and manufacturing entities. Relevant scholars have carried out much research and practical work around the perception and access to manufacturing resources.

It is also applicable for intelligent manufacturing with software-defined manufacturing service (SDMS) as the most apparent feature. However, driven by IIoT and SDMS, the three-level architecture requires more practical enabling technologies to satisfy the requirements of mass personalization[5]. This paper combines edge computing and microservice, and develops an intelligent edge gateway. The edge gateway can realize the dynamic management of manufacturing resources.

(1) Edge gateway

The role of the edge gateway is highly emphasized in the white paper on discrete manufacturing edge computing solutions released by the Alliance of Industrial Internet. The edge gateway can convert the industrial protocols of various manufacturing entities into standard OPC UA and other communication protocols[6]. Compared with traditional industrial gateways, edge gateways split each service component into finer granularity[7]. It enables the gateway upper-layer and the cloud platform to communicate using a unified protocol and information model. It also reduces the coupling between service modules and dramatically improves the scalability of the gateway system.

(2) Microservice architecture

The edge gateway adopts a cloud-native microservice architecture. It integrates lightweight container management and virtualization technologies to build a unified heterogeneous data integration platform. Microservices can realize distributed deployment as a new service type compared with traditional service-oriented architecture (SOA). More sensor accesses can be supported through the horizontal expansion of the edge gateway and solve massive connections in IIoT[8-9].

In the manufacturing workshop, it is necessary to add data collection and control terminals for each device to realize the perception and access of manufacturing resources. The SOA model can hardly achieve rapid reconfiguration of the manufacturing system on the edge gateway software architecture. The microservice architecture is a new paradigm for these large-scale entity clusters by contrast.

This paper implements an intelligent edge gateway that combines edge computing and microservice architecture. First, the problem of data blocking caused by the heterogeneity of IIoT is solved by the standard protocol. Second, the implementation of microservice architecture solves significant information interaction delays[10].

The rest of this article is organized as follows. The system architecture of the edge gateway is first outlined in the cloud customization environment. The authors' group describes the critical technology for the physical manufacturing entities to generate virtual manufacturing resources in the edge gateway. Then the authors' group proposes an edge gateway operating mechanism based on microservice architecture. Finally, a prototype system of the edge gateway application in the production site is introduced.

1 System Architecture

A gateway is essential for realizing edge computing-oriented distributed manufacturing resource access in the cloud manufacturing scenario. Compared with monolithic architecture and SOA, microservices are optimized in system complexity. Therefore, a gateway based on microservice architecture and edge computing is more suitable for the fragmentation control of distributed manufacturing resources than SOA and cloud computing.

The proposed intelligent edge gateway has a four-layer system architecture as a middleware platform linking manufacturing resources and the cloud platform. After analyzing the foundation of the existing edge gateway architecture, we propose a system architecture based on the microservice concept, as shown in Fig.1. Specifically, the first layer is the protocol adaptation layer, which is mainly responsible for accessing heterogeneous control systems as the essential service. Secondly, the basic service layer mainly completes service management (e.g.,

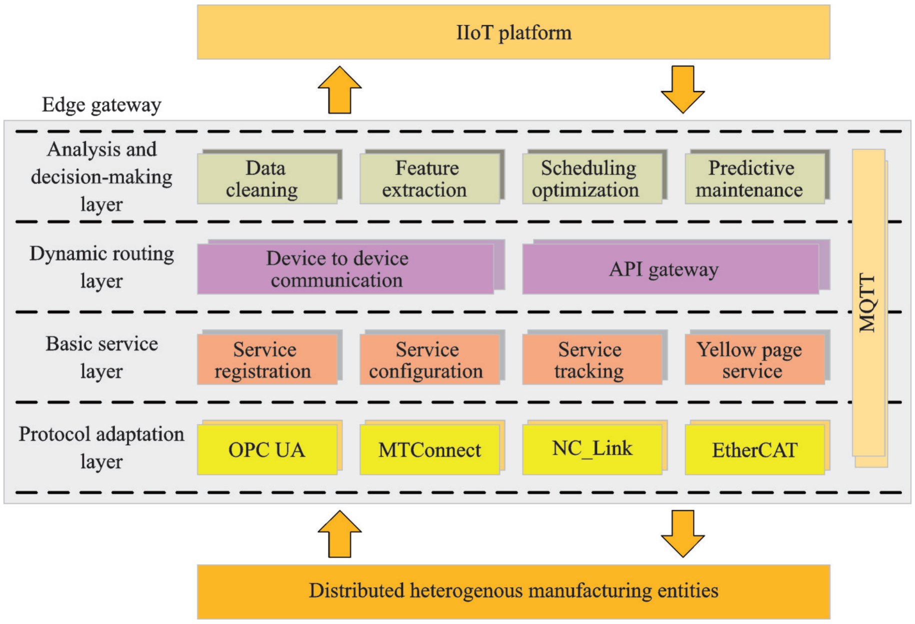

Fig.1 Architecture of the edge gateway based on microservice

service registration, service configuration, and service tracking) and API service isolation. Thirdly, the dynamic routing layer realizes real-time information interaction between the horizontal devices and the vertical cloud platform. Finally, the analysis and decision-making layer completes resource allocation and scheduling optimization by analyzing the real-time status of underlying physical entities.

The granularity is further refined based on these four essential services[11]. Each basic service can be split into a series of smaller microservices.

(1) Protocol adaptation layer

The protocol adaptation layer is mainly responsible for linking the heterogeneous manufacturing entities. These entities usually use different industrial protocols for data transmission. The protocol adaptation layer can be compatible with standard industrial protocols such as OPC UA, MTConnect, and NC_Link[12-13]. When the analysis and decision-making layer request is sent to the protocol adaptation layer, this layer converts the request into a format that can be recognized by the driver to control the underlying sensors. In order to improve the system's stability, the protocol adaptation layer adopts the design of redundancy and overtime disconnection.

(2) Basic service layer

The basic service layer is essential to provide necessary support services for upper-layer applications. The perfection of basic services premises the stable and efficient operation of upper-level applications. In the edge gateway architecture, the basic service layer mainly includes four parts: Service registration, service configuration, service tracking, and yellow pages. Specifically, as the first and primary roles, service registration refers to registering the service at the edge gateway for subsequent task scheduling when the device is powered on or restarted after a breakdown. Service configuration completes the standardized description of primary attributes such as processing capabilities and physical attributes. Service tracking realizes real-time feedback of current processing progress, equipment status, and other parameters. The yellow pages service provides all resources connected to the gateway, and the device can be quickly found based on the IP address.

(3) Dynamic routing layer

The function of the dynamic routing layer is to realize information interactions within the edge gateway. The purpose of the dynamic routing layer is to achieve edge-cloud collaboration. The dynamic routing layer mainly includes two services. One is the information interaction between devices in the gateway, which can be directly communicated by querying the microservice of yellow page. The other is the information interaction between the edge gateway and the cloud platform, which is implemented by the API gateway.

Furthermore, the API gateway is the entrance to access the entire edge gateway system. The cloud platform requests the API gateway, and then the API gateway transmits the request to the corresponding microservice. After the microservice responds, the API gateway returns the result to the cloud platform finally.

(4) Analysis and decision-making layer

The analysis and decision-making layer is mainly to run some intelligent edge gateway applications. Those operations such as data cleaning and feature extraction are realized by defining some commonly used data processing methods on the edge gateway. Resource allocation and scheduling optimization are the core part of applying computing tasks to the edge gateway. The scheduling optimization is achieved through the interactive negotiation of the dynamic routing layer in the gateway[14]. In the scheduling optimization, the best resource allocation is determined through continuous information interaction between microservices. Through self-organization and negotiation, this paper designs a global task scheduling decision mechanism at the edge gateway. The negotiation between the microservices completes the dynamic scheduling of manufacturing resources.

2 Kernel Microservices of Edge Gateway

After completing the architecture design according to the functional attributes of the edge gateway in cloud manufacturing, it is necessary to implement the enabling technology of each layer. The goal of these techniques is to combine the microservices with the intelligent edge gateways.

The most critical role of edge gateway in cloud manufacturing is data transformation, ontology modeling, information interaction, and resource allocation. A manufacturing entity can generate a self-organizing virtual network resource in the edge gateway through protocol conversion, ontology information model, and information interaction. This virtual manufacturing resource can realize the service encapsulation and virtualization access of physical entities[15].

2.1 Data transmission microservice

In cloud manufacturing, the ubiquitous perception of distributed manufacturing resources is the first issue to be solved. However, manufacturing resources cannot directly interact with each other due to the heterogeneity of communication protocols. Therefore, the protocol adaptation microservice adopts the adapter/agent mode to solve the multi-protocol adaptation problem. The adapter/agent mode configures special adapters for heterogeneous control systems to achieve resource information collection and standard format conversion. And then, the data transmission microservice releases these standard data through the agent to realize workshop entities' information interconnection and monitoring[16]. Finally, the adapter/agent program will be encapsulated into a protocol adaptation microservice, which runs in the edge gateway. The microservice of protocol adaptation is composed of the primary function and various functional modules. These functional modules include general control, monitoring, database, and special modules such as NC code and AGV path planning. The model of data transmission microservice in the protocol adaptation layer is shown in Fig.2.

(1) Main module

The main module of the data transmission microservice contains the adapter's overall working logic and exception handling mechanism. The main module is responsible for the connection, communication, and management of the interfaces of the resource adaptation model. In addition, it also monitors and responds to the manufacturing system interface.

(2) Control module

The control module in the data transmission microservice contains some essential functions for connecting and controlling the corresponding underlying entities. The control module can realize the critical functions in the traditional mode, such as program start and reset.

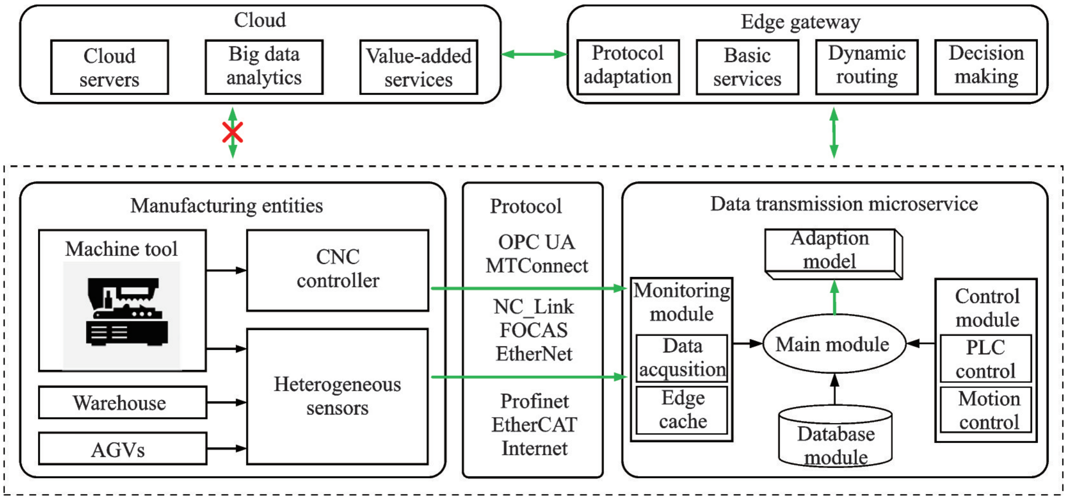

Fig.2 Model of data transmission microservice in protocol adaptation layer

(3) Monitoring module

The monitoring module contains functions such as information collection of the underlying manufacturing entity and status monitoring. Some of these information collection functions can also be obtained through the equipment manufacturer's dynamic link library.

(4) Database module

The database module contains standard database operation functions, such as the connection between the device adaptation model and the underlying device. In addition, the database module also has functional operations such as data adding, deleting, modifying, and querying.

(5) Other dedicated modules

With the exception of the three basic modules mentioned above, the data transmission microservices of the edge gateway also have other specialized modules, such as NC code modules and AGV path modules.

2.2 Ontology information microservice

In order to achieve unified control of the underlying physical manufacturing resources by the edge gateway, these manufacturing entities need to be modeled based on standardization. In this paper, the ontology-based resource modeling enables the underlying equipment to access the IoT manufacturing system and it is efficiently invoked by the upper-layer applications. It is necessary to abstract the underlying equipment and establish its ontology model[17]. These devices can be controlled uniformly by establishing a standard ontology information model.

The upper-layer application of edge gateway is concerned with the functional attributes of the underlying equipment. Therefore, this paper takes the functional model of the underlying equipment as the main discussion object and ignores the knowledge of other fields such as structural models and behavioral models[18]. Finally, the ontology information microservice establishes the ontology information of available equipment according to the functional attributes of manufacturing resources.

CNC machine tools are the most common manufacturing service providers as the lowest manufacturing entity in cloud manufacturing. Although heterogeneous CNC systems have different control logics, they all play the same role in the manufacturing system. The structure of an ontology-based information model of a simple CNC machine tool is shown in Fig.3. For CNC machine tools, the ontology information model can be simplified as essential equipment with four functions: Workpiece processing, processing time estimation, fixture closing, and fixture opening. Among them, the processing time estimation provides important decision-making parameters for the resource allocation microservice. Each CNC ontology information model has the same effect as the physical operation through control instructions and feedback messages. Taking the interactive command of the access control model based on the ontology as an example, the interactive command consists of three parts, including an object, an action, and enabling information (if needed, Fig.3). Each interactive instruction must return the execution status and determines whether the execution is successful. Then, it can be used as a link to access specific manufacturing resources, such as executing machining programs (machining_workpiece), estimating makespan (evaluate_machining_time), and releasing and clamping workpieces (release_workpiece, grab_workpiece), etc. In addition, if a local manufacturing resource is activated, it is known that the edge gateway has requested the job to be machined (run) from the first step until the end of all task steps.

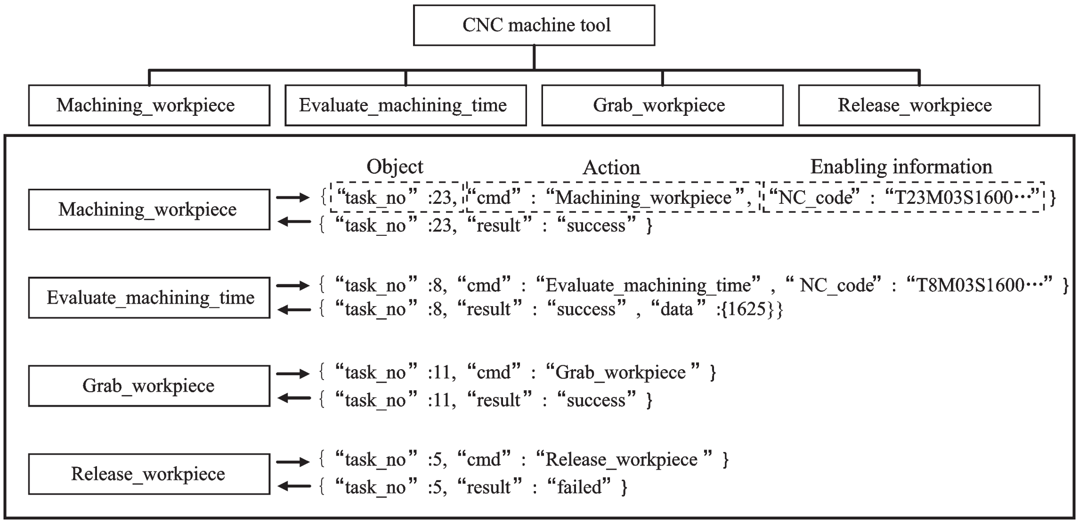

Fig.3 Structure of an ontology-based information model of a simple CNC machine tool

2. 3 Information interconnection microservice

In the intelligent edge gateway, the unification of the typical industry protocol is realized through the protocol adaptation layer. On this basis, dynamic manufacturing resources can realize real-time information interaction between devices through the dynamic routing layer of the edge gateway.

The underlying device establishes a connection with the cloud platform through the edge gateway. All kinds of interaction information generated by the manufacturing resources are directly sent to the edge gateway. Therefore, the interactive information in the edge gateway mainly includes device-to-device and edge-to-cloud interaction information. The interaction information contains the dialog initiator ID, the executor ID, and the information content.

For device-to-device communication, the edge gateway will complete the following steps after receiving the interaction request. First, it is necessary to unpack the interaction information, obtain the ID of the conversation initiator, and record the instruction number in the message content. Then, the information interaction finds the IP address and port number in the yellow pages microservice through the receiver ID and forwards the message content to the receiver.

For edge-cloud information interaction, the edge gateway adopts a direct connection. The forwarding of crucial tasks no longer depends on the service terminal through the emerging network communication technology. Due to the near-field gain and single-hop gain between cloud edges, the end-to-end interaction provides lower latency time and higher reliability communication services in the cellular network environment[17].

The end-to-end information interaction in cloud manufacturing is shown in Fig.4. The cloud platform usually does not directly interact with the underlying physical entity in the actual execution process. Considering the requirements of security and other aspects, the cloud platform and the underlying resource need to use edge gateways to perform operations such as message encryption and forwarding.

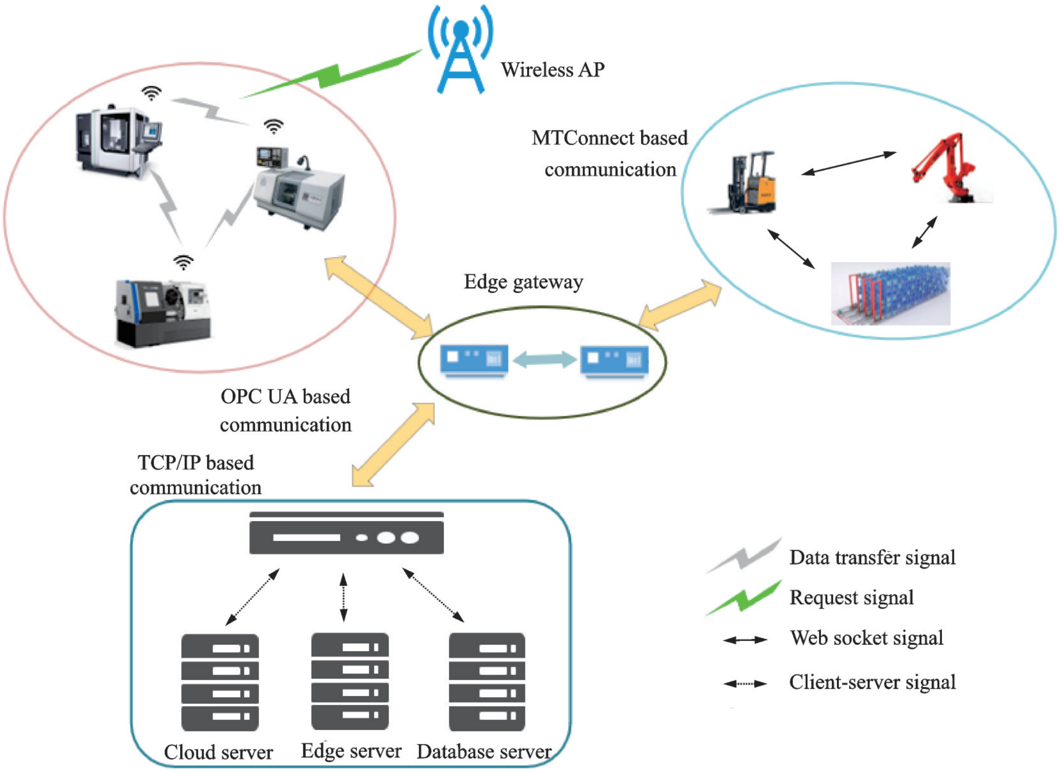

Fig.4 End-to-end communication in cloud manufacturing

2.4 Resource allocation microservice

Those resources can only passively receive scheduling decisions from the cloud platform as an independent individual in the traditional centralized manufacturing mode. It is a great challenge to cope with frequent production disturbances in an increasingly variable and large-scale personalized customization environment. Therefore, the proposed edge gateway adopts the negotiation-based active scheduling method to complete the dynamic manufacturing resource allocation. With the help of IIoT, the physical manufacturing entity generates a virtual network resource through the edge gateway (e.g., protocol adaptation, ontology information modeling, and service registration). The virtual network resource plays a crucial role in improving the interconnection of manufacturing equipment in the workshop and adapting the manufacturing process promptly.

Fig.5 shows a flowchart of resource allocation.

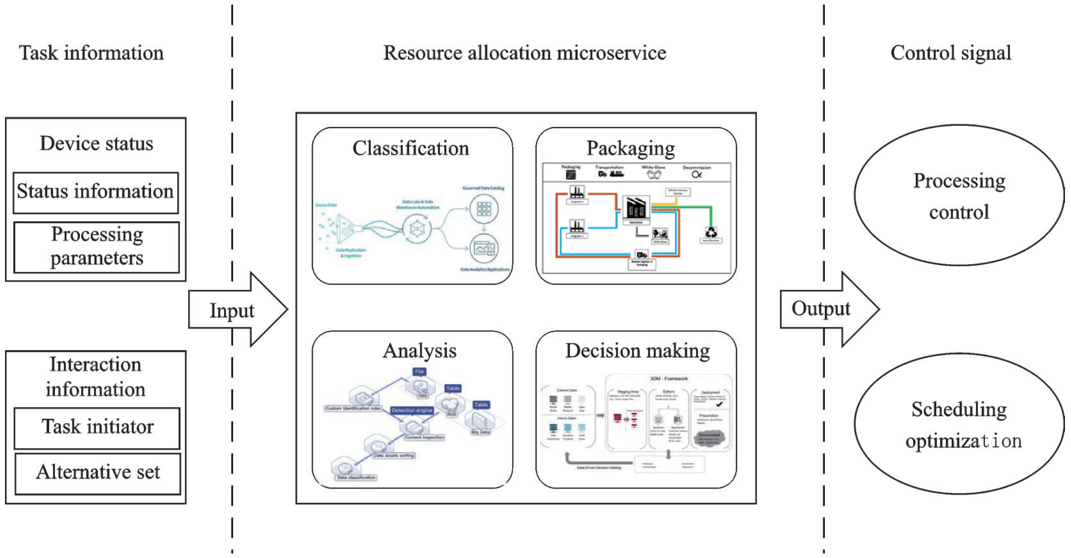

Fig.5 Negotiation based scheduling mechanism

There are two primary sources of decision-making information for virtual network resources. One is the physical manufacturing entity status obtained through the protocol adaptation layer. The other comes from device-to-device communication. That information is passed to the edge gateway analysis and decision-making layer. In detail, the information is classified and mainly divided into the processing task information related to the physical manufacturing entity's action information and the task information. Second, according to the information classification results, the resource allocation microservice analyzes the processing status and workshop environment. Finally, the resource allocation microservices make scheduling optimization based on optimization goals such as production cost and resource consumption. Thus, the coordinated allocation and dynamic scheduling of resources are realized, and the manufacturing efficiency is improved.

3 Case Study

The information interaction of large-scale manufacturing resources has brought enormous network communication pressure in cloud manufacturing. During the interaction, different data schemas, interfaces, and communication protocols complicate these transfers. Therefore, this paper proposes the real-time ubiquitous perception and access of manufacturing resources and finally implements an intelligent edge gateway based on the microservice architecture.

Take the self-organizing IoT manufacturing system as an example. The prototype system and edge gateway architecture are shown in Fig.6. This production line has typical features of cloud manufacturing, including service encapsulation and virtualization access of physical entities. We use the IoT manufacturing line to prove the effectiveness of the proposed edge gateway system.

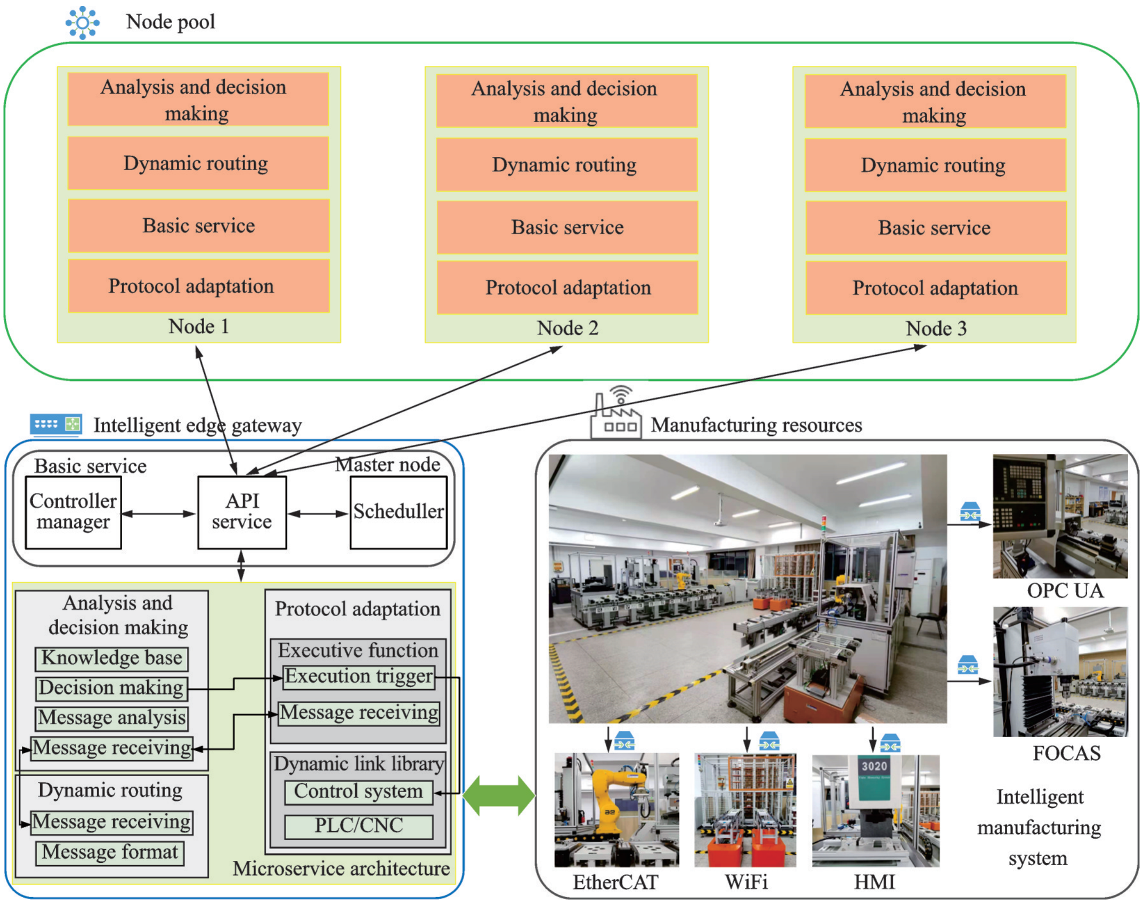

Fig.6 Intelligent manufacturing prototype system

We have developed two modes of edge gateway systems. The original one is developed with a service-oriented architecture, and the software system is particularly complex. Currently, the gateway is reconstructed with a microservice architecture, which significantly improves the system's stability.

In the microservice-based edge gateway, each manufacturing entity will register a computing node in the pool online and inherit a series of microservices from the parent master node. Then, the mapping of manufacturing entities to manufacturing services is completed through operations such as protocol adaptation, service registration, and activation of heartbeat packets.

The node pool is similar to a virtual manufacturing line, and each node corresponds to a manufacturing entity. In contrast, that the nodes interact and communicate with each other completes the self-organizing production of task orders through real-time information interaction[19-20].

3.1 Prototype system

The basic workflow of the self-organizing IoT manufacturing system is as follows. First, consumes customized machined parts online. Then the order data is sent to the edge gateway system after resource allocation in the cloud platform. In our prototype system, all manufacturing resources are task-driven and can complete tasks in a self-organizing negotiation manner. Due to the heterogeneity of the manufacturing element control system and the complexity of scheduling tasks, edge gateways in smart factories are vital. Those physical manufacturing entities such as CNC machine tools generate corresponding virtual network resources through the edge gateway. These virtual units run in the edge gateway in microservices and finally realize negotiation and scheduling through information interaction.

The interaction between the manufacturing resources and the cloud is carried out in the dynamic routing layer of the edge gateway, which contains two parts of the horizontal device-to-device communication and the vertical devices-to-cloud one. Parts of the information exchange process are as follows.

(1) Device-to-device communication: After each device is online, the cloud manufacturing system registers services, and the edge gateway assigns an IP address and adds it to the Yellow Page service. During the manufacturing execution stage, the interaction initiator will access the gateway's Yellow Page service to query the object entity's IP address, package the information and send it through the gateway.

(2) Device-to-cloud communication: For the security of the industrial control network, the manufacturing resource cannot directly access the cloud. The edge gateway encapsulates and encrypts the interaction information of the manufacturing entity and sends it to the cloud platform.

3.2 Improvement of microservice based edge gatewate

In the self-organized IoT manufacturing system built above, the relevant functions of the edge gateway are verified. These functions mainly include the interconnection and interoperability between devices and the dynamic reconfiguration of the manufacturing system. By comparing the edge computing and microservice architecture models proposed in this paper with SOA, the improvement of the edge intelligent gateway in actual production is verified. The main features of the proposed edge gateway are summarized as follows.

(1) System scale

The advantage of microservice-based edge gateways is program scale. Compared with the original service-oriented architecture, the number of codes for the edge gateway of the microservice architecture has been reduced from more than 50 000 lines to 10 453 lines.

(2) Communication latency

During end-to-end information interaction in the manufacturing system, communication latency has always been a concern. The proposed microservice-based edge gateway generates virtual network resources by protocol adaption and ontology information modeling. The information interaction between devices is converted from the physical layer to the network layer interface. This kind of edge gateway based on microservice architecture has dramatically improved network bandwidth, latency, redundancy, and security.

(3) Dynamic reconfiguration

Another improvement of microservice architecture compared with SOA is the efficiency of system reconstruction. In the traditional SOA architecture, the offline and re-online of a single device can easily cause a system breakdown. In contrast, the edge gateway based on microservice architecture can realize the dynamic management of manufacturing resources.

4 Conclusions

The information interaction of large-scale manufacturing resources has brought enormous network communication pressure in cloud manufacturing. During the information interaction, different data schemas, interfaces, and communication techniques complicate these transfers. Therefore, this paper proposes the real-time perception and access of manufacturing resources and finally implements an intelligent edge gateway based on the microservice architecture. Without a large-scale upgrade of automation equipment, digitization can be effectively improved by adding edge gateways and edge data collection terminals.

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Acknowledgements This study was supported by the National Key Research and Development Program of China (No.2020YFB1710500), and the Primary Research & Development Plan of Jiangsu Province(No.BE2021091).

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Author contributions Mr. **WANG Liping** conducted the study and wrote the paper. Prof. **TANG Dunbing** completed the interview and assessment. Mr. **NIE Qingwei** designed the case study. Mr. **SONG Jiaye** and Mr. **LIU Changchun** contributed to the conclusion and background. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: WANG Jing)

云制造环境中一种基于微服务架构的智能边缘网关实现方法

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摘要：云制造已经成为现实。它需要通过工业物联网对异构制造资源进行感知和接入，并进行深度的数据分析。然而，云计算和面向服务的体系结构在动态制造资源管理方面略显不足。本文将边缘计算和微服务技术相结合，开发了面向云制造的智能边缘网关，通过边缘网关可访问分布式制造资源，同时实现云边协同。智能边缘网关为当前制造场景下的复杂资源泛在感知提供了解决方案。最后，开发了一个原型系统并验证了智能边缘网关的有效性。

关键词：边缘计算；智能网关；微服务架构；云制造