Edge Computing in IoT-Based Manufacturing

Baotong Chen, Jiafu Wan, Antonio Celesti, Di Li, Haider Abbas, and Qin Zhang

Abstract

Edge computing extends the capabilities of computation, network connection, and storage from the cloud to the edge of the network. It enables the application of business logic between the downstream data of the cloud service and the upstream data of the Internet of Things (IoT). In the field of Industrial IoT, edge computing provides added benefits of agility, real-time processing, and autonomy to create value for intelligent manufacturing. With the focus on the concept of edge computing, this article proposes an architecture of edge computing for IoT-based manufacturing. It also analyzes the role of edge computing from four aspects including edge equipment, network communication, information fusion, and cooperative mechanism with cloud computing. Finally, we give a case study to implement the active maintenance based on a prototype platform. This article aims to provide a technical reference for the deployment of edge computing in the smart factory.

Introduction

In the context of intelligent manufacturing, the proliferation of terminal network devices has given rise to new challenges for operation and maintenance, scalability, and reliability of the data centers. The growth of edge computing has moved the computing from centralized data centers to the periphery of the network. Edge computing aims to address these challenges by creating an open platform with the capability of integrating core capabilities such as networking, computing, storage, and application. It has enabled intelligent services close to the manufacturing unit to meet the key requirements such as agile connection, data analytics via edge nodes, highly responsive cloud services, and privacy-policy strategy [1, 2]. Edge computing can make full use of embedded computing capabilities of field devices to achieve equipment autonomy based on distributed information processing. Furthermore, edge computing supports the need of digital manufacturing enterprises for rapid configuration of the smart factory, which must adapt to personal demands of users and dynamic changes in production conditions.

Research on edge computing is progressing rapidly. Due to the limitation of the cloud platform, Lopez *et al.* [3] considered that edge computing is needed for moving the data and services from centralized nodes to the edge of the network. Patel *et al.* [4] outlined the novel approach of using the intelligent edge (e.g., Raspberry Pi) for Internet of Things (IoT) data analytics. Its use case can be found in intelligent manufacturing. Condry *et al.* [5] introduced a model using smart edge IoT devices for safer, rapid response with industry IoT control operations. As IoT application to the industrial domain is spreading, Georgakopoulos *et al.* [6] proposed a roadmap combining cloud edge computing for IoT-based manufacturing. Suganuma *et al.* [7] proposed multiagent-based flexible edge computing architecture for a large-scale IoT system. Byers [8] provides a review of the architecture, use case, and requirements for fog-enabled IoT networks. Both of them are important references for the deployment of edge computing in IoT-based manufacturing. Satyanarayanan [9] pointed out that the emergence of edge computing has enabled the cloud services for mobile computing, scalability, and privacy policy. However, the reference architecture for IoT-based manufacturing has not yet been proposed. Edge computing and its role in the Industrial Internet of Things (IIoT) application should be established.

Industrial applications in the domain of IoT require characteristics such as location awareness and low latency. Edge computing, which is implemented at the peripheral devices on an IoT network, has the ability to support these requirements of mobility and geographic independence. Computing's physical proximity to a mobile device makes it easier to achieve low end-to-end latency, high bandwidth, and low jitter to services located at the network edge. Edge computing is being introduced into IoT-based manufacturing. The scope of edge computing extends the range of an IoT embedded device with capabilities of limited storage, cache, and processing to the edge near the terminal infrastructure (e.g., Raspberry Pi and Arduino board). The contributions of this article can be summarized as follows:

- In view of the typical applications of edge computing in the domains of intelligent manufacturing, this article proposes a novel system architecture from four perspectives: the device domain, the network domain, the data domain, and the application domain.
- With the focus on the development of edge-specific field devices, this article discusses how to achieve efficient information interaction, heterogeneous data fusion, and a cooperative mechanism with the cloud platform. Some related use cases are also presented for IoT-based manufacturing.
- Based on the typical characteristics of edge computing in IoT-based manufacturing, this

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Due to the lack of the flexible configurable middleware, it is challenging to implement a flexible adjustment to the equipment in order to cope with the changing manufacturing status. However, the popularity of IIoT requires a more open mode in the industrial field, especially for safe remote access, periodic maintenance, and industrial big data analysis.

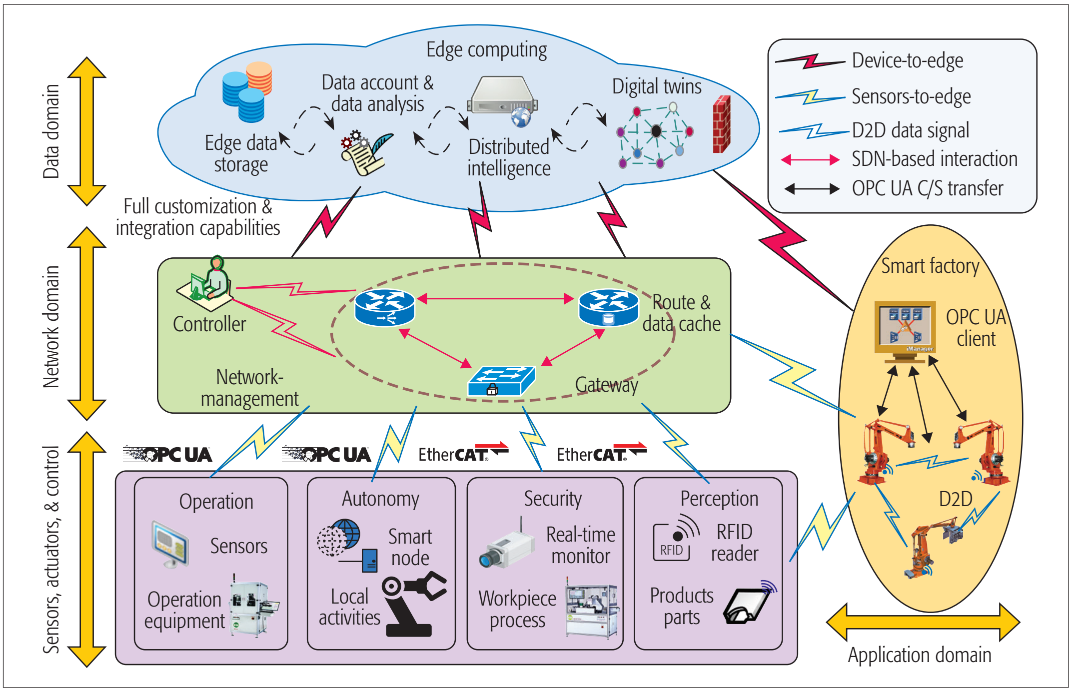

Figure 1. Architecture of an edge computing platform in IoT-based manufacturing.

research develops a laboratory prototype platform, and conducts experiments for the active maintenance of equipment in smart factory. The experiments demonstrate the advantages of edge computing for business agility and bandwidth optimization.

The rest of the article is organized as follows. We propose a system architecture for the application of edge computing in IoT-based manufacturing. We present the role of edge computing in manufacturing scenarios involving devices, networks, data, and the manufacturing cloud. We present the combination of edge computing with the typical industrial applications to achieve active maintenance of the production line. The final section concludes our work.

System Architecture

With the goal of proposing a novel application scenario for edge computing, we present the system architecture of edge computing in an IoT-based manufacturing scenario. As shown in Fig. 1, the architecture is divided into four fields: the device domain, the network domain, the data domain, and the application domain.

•The device domain is either embedded in, or located close to, the field devices such as sensors, meters, robots, and machine tools. The device domain should support a flexible communication infrastructure and be able to establish standardized communication models to support various types of communication protocols. Nodes in an edge computing network must have the ability to compute and store data to dynamically adjust the execution strategy of the industrial equipment based on sensor inputs. The information model is built on the edge computing nodes, and includes mainstream protocols such as OLE for Process Control Unified Architecture (OPC UA) [10] and Data Distributed Service (DDS). It is deployed to realize the unified semantics of information interaction, and ensure data security and privacy.

•The network domain connects the field equipment to the data platform in a flat manner. In IoT-based manufacturing, the network domain uses software defined networking (SDN) [11] to achieve separation between the network transmission and the control. Due to the necessary time sensitivity of the task data, a time-sensitive network (TSN) protocol is applied to process the sequence of network information and to provide the general standards for maintaining and managing the sensitive time nodes.

•The data domain in the data origin provides services such as data cleaning and feature extraction, which improves the availability of the heterogeneous industrial data. This also allows the implementation of pre-defined responses that can be based on the real-time IoT data. The abstract data at the device terminal end is provided to the remote service center for the virtualization of the manufacturing resources.

•The application domain inherits the applications of the manufacturing cloud at the network edge. It integrates the key technologies among the network, data, computing, and control. The application domain enables edge computing to provide general, flexible, and interoperable intelligent applications. Components such as service composition, based on the requirements of the manufacturing process, allow the dynamic management and optimal scheduling of field equipment.

The device domain supports real-time interconnections and the deployment of intelligent applications to field devices. It provides an important foundation for the upper layers of the application. The network domain is useful for multiple purposes such as the real-time transmission of heterogeneous industrial data, the control of complex network states, and the convenient access to manufacturing resources. It provides a platform for performing inter-connection, information interaction, and data fusion on the edge computing nodes. The data domain also provides data optimization services. One of its main tasks is to ensure consistency and integrity of the data. The application domain provides intelligent application services for edge computing, which allows the independent implementation of local business logic at the peripheral devices. The domain also provides open interfaces for the device domain and the network domain to realize edge industry application. The proposed edge computing architecture, presented in Fig. 1, makes full use of the embedded computing capabilities and ensures the autonomy of the system and the manufacturing equipment while following a distributed computing paradigm. Furthermore, the edge computing framework cooperates with the remote data center to realize intelligent terminals for the manufacturing system.

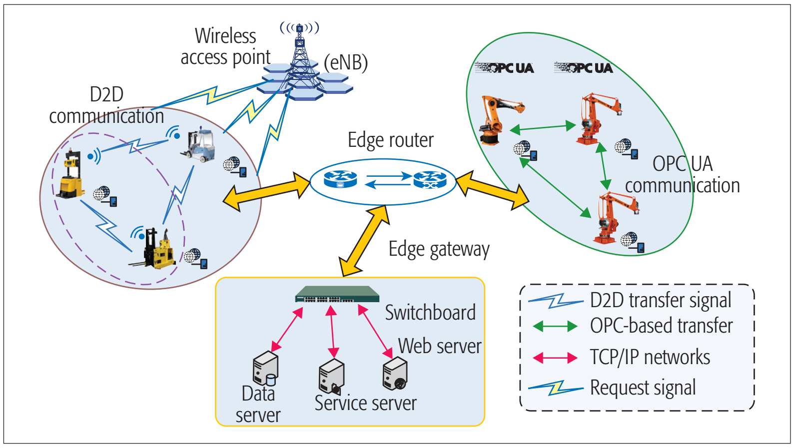

Figure 2. Efficient information interaction in IoT-based manufacturing.

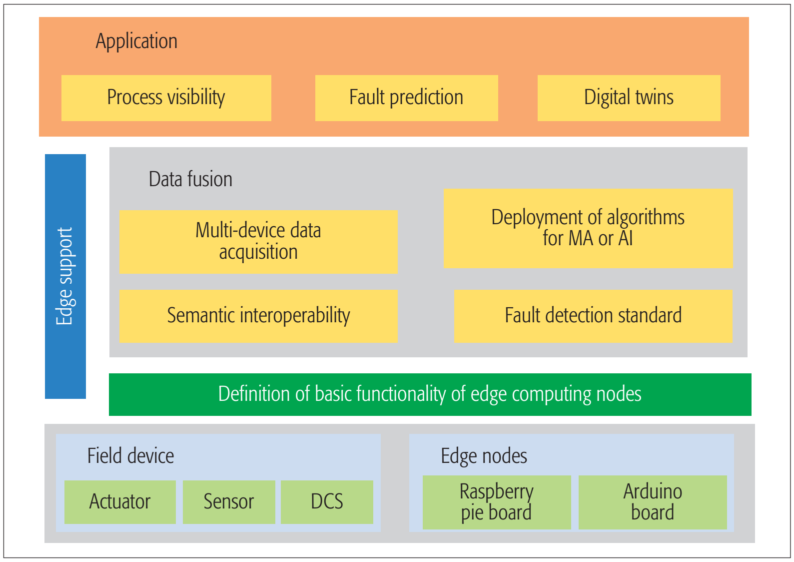

Figure 3. Architecture of an edge-enhanced data fusion system.

The Roles of Edge Computing in IoT-Based Manufacturing

In view of the dimensions of the manufacturing system, edge computing can be located either at the equipment level, at the control level, or at the workshop level. It may support individual stages such as system integration, interconnection, information fusion, or the entire life cycle of the manufacturing process. The deployment of edge computing transforms the system to allow flexibility in adapting to changes in the resources of the production line, which can in turn promote the development for IoT-based manufacturing.

Edge-Specific Device Supporting Network Middleware

The whole IoT-based manufacturing architecture is like a pyramid that can be simply divided into the device layer, the control layer, and the network layer. There is a strong interaction between the underlying manufacturing equipment and the affiliated services. Due to the lack of flexible configurable middleware, it is challenging to implement flexible adjustment to the equipment in order to cope with the changing manufacturing status. However, the popularity of IIoT requires a more open mode in the industrial field, especially for safe remote access, periodic maintenance, and industrial big data analysis. The emergence of edge computing attempts to deal with this challenge by transforming the computing model of intelligent manufacturing from a centralized control model to a distributed processing model. Additionally, the edge computing nodes support the plug and play of new equipment and rapid replacement in case of failure. One challenge in the IIoT framework is the ubiquitous compatibility problem due to the existence of a diverse number of protocols. Therefore, to deal with this diversity, edge computing nodes provide multiple access modes within their modular network interfaces. Furthermore, the format of transmission payload is modified to adapt to different communication protocols and to facilitate easy information exchange between the equipment. It also allows the flexible adjustment of production plans, and supports rapid deployments of new processes.

Edge computing improves the terminal intelligence of manufacturing equipment. The goal is to not only allow the IIoT devices to perform business logic analysis and autonomous computing, but also to give them the capability to optimize and adjust their execution strategies in real time. Edge computing nodes also make it possible to implement active maintenance at the edge of IIoT. It enables the acquisition of real-time and accurate state of the equipment. In the same way, some of the diagnostic tasks run on the manufacturing cloud can be offloaded to the edge computing nodes, which decreases the time delay needed in performing these diagnoses, and enables proactive maintenance. This decreases the maintenance time and reduces the application monitoring pressure of manufacturing cloud. In general, edge computing nodes are integrated into IIoT, making the embedded control more powerful and improving the scalability of the network.

Edge-Enhanced Information Interaction

IIoT is deployed to achieve seamless communication between manufacturing resources and different control systems. Edge computing in IIoT systems provides important support for the applications at the network edge. As shown in Fig. 2, the OPC UA provides protocols and services [10], which helps to realize an integrated information model independent of the network

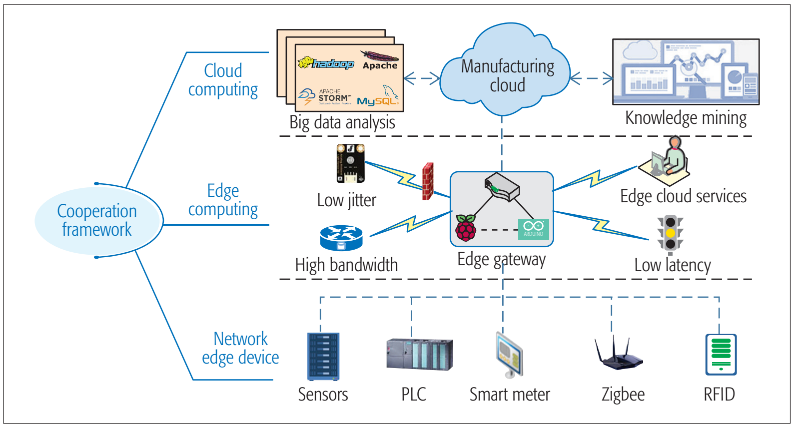

Figure 4. Cooperation mechanism in IoT-based manufacturing.

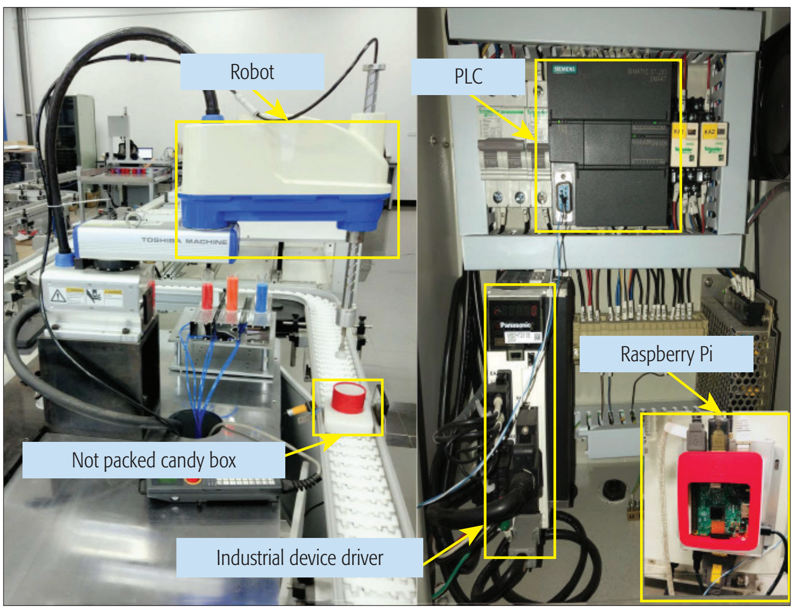

Figure 5. A prototype platform with edge computing equipment for IoT-based manufacturing.

facilities. This allows the system to achieve ubiquitous perception and semantic interoperability of manufacturing resources. Edge computing nodes are being implemented to the smart factory for the fast configuration of the OPC UA technology. The server of OPC UA can be built with edge computing nodes, thus removing the infrastructure obstacles that are present in traditional manufacturing equipment. The emergence of the application of information technologies (e.g., SDN and network functions virtualization) in intelligent manufacturing has helped to break the limitation of traditional network architecture. These systems therefore meet the requirements of IIoT by providing massive connections, automatic operation and maintenance, and advanced network security policies [11, 12]. The deployment of edge computing is generally in the form of a virtual machine or a software container on the gateway, which decouples network connections and supports third-party applications. While SDN makes the industrial network highly reconfigurable, it cannot meet the requirement of low latency. Recently, time-sensitive networks (TSNs) have been suggested as a new solution for real-time IIoT. It is a set of protocol clusters located at the data link layer to decrease the network uncertainty of the underlying architecture. Edge computing is introduced in these scenarios to act as the time-aware scheduler. It ensures that the network is sensitive to the time factor requirements of the different data tasks. Edge computing provides real-time performance on the time node and processes sequences of information interaction.

Mobile edge computing (MEC) is a networking application and edge service based on intelligent interaction at the equipment terminal. The deployment strategy of MEC has the advantages of low latency, high bandwidth, and a lightweight network. MEC has the ability to provide more accurate services in real time by accessing wireless network information and location information [13]. In addition, device-to-device (D2D) communication technology has also been extended to the industrial field [14]. This allows convenient resource allocation by means of the base station in the smart factory. Mobile equipment can interact with each other through the wireless network infrastructure. Furthermore, in the case of no network coverage, devices can piggyback their connections off nearby devices, which can form local subnetworks, and then access the core network through these intermediate connections.

Edge-Enhanced Data Fusion and Advanced Analytics

Fusion of different types and sources of data is an important step for data acquisition and intelligent control in the management of complex industrial processes. Edge computing can enhance the capability of data fusion at the network edge. Figure 3 shows the architecture of an edge-enhanced data fusion framework. Edge computing can make full use of the sensor resources at the peripheral network devices. The complementary and redundant information obtained from the sensors in space and time are combined according to pre-defined optimization criteria and algorithms. This improves the consistency of the interpretation and the analysis of the detected event. Based on a knowledge base, a self-learning mechanism can perform dynamic reasoning and generate responses. Edge computing nodes can be deployed to extract features from the sensor signals by applying techniques such as time series analysis, frequency analysis, and wavelet analysis. An artificial intelligence (AI) or machine learning (ML) model can be run on the edge computing nodes to utilize the characteristic data to make predictions and to subsequently update the knowledge base. Dynamic reasoning at the edge can be performed according to the updated knowledge and received data. This allows intelligent decision making at the network edge.

The implementation of fine-grained data acquisition is easy to realize at the peripheral equipment, and the different streams of the original data can be directly fused. The fused data is more informative and synthetic than the original inputs. It is possible to provide IoT-based computational resources in a similar vein as the operating system or software containers offered on the edge nodes. The manufacturing process can be visualized based on advanced data visualization technologies. This would allow the system to forecast failures and perform active maintenance. Additionally, detection devices are used to collect all

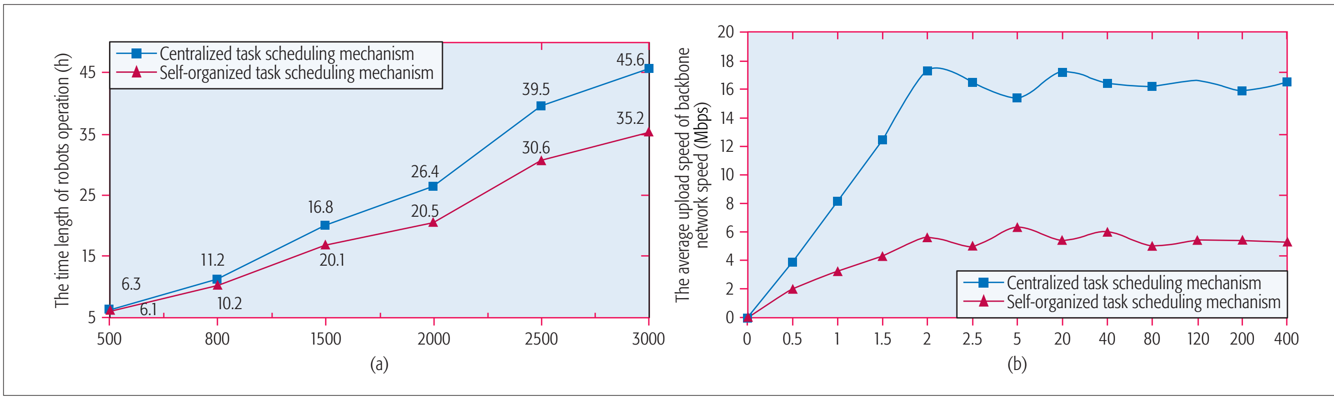

Figure 6. Experimental results of the equipment scheduling mechanisms: a) order quantity in a candy packing line; b) running time of the candy packing line (min).

the equipment execution data, extract features based on the data fusion strategies implemented at the edge computing, and abstract the functions of the equipment to construct a digital twin of the intelligent equipment. From the perspective of each server, edge computing mainly implements intelligent local distribution of computing resources in the IIoT. It maps the intelligent equipment in virtualized manufacturing environments and supports data centers to build digital plants. The digital twins can then be used for direct product manufacturing, process optimization, and cost reduction.

Cooperation Mechanism between Cloud Computing and Edge Computing

The combination between cloud computing and edge computing enables the digital transformation of manufacturing. As shown in Fig. 4, such a cooperation mechanism can be described as follows.

•Since the focus of the system is on providing real-time or short-term data analysis, edge computing can better support the real-time processing and performance evaluation of local businesses. This reduces network pressure, and improves data security and privacy protection.

•Cloud computing, on the other hand, does not focus on real-time or short-cycle data analysis. Its focus is to implement big data analysis and knowledge mining from the data obtained from edge computing networks. It plays an important role in periodic maintenance, decision support, and other activities that do not necessarily need to be performed in real time.

•Since edge computing is performed close to the execution unit, the edge computing nodes act as collection units of heterogeneous data and move complex optimization problems to the cloud. They supply the cloud computing frameworks with the necessary high value data that can better support the cloud application (e.g., big data analysis). The decision model through the optimization of the business rules can be established on the edge nodes for improving the efficiency and performance of the cloud.

As the number of sensors embedded in devices increases, the amount of data grows exponentially. Implementing real-time control loop feedback becomes more complex, and the analysis of all the data streams to generate decisions becomes more time-consuming. Extending the requirements for processing capacity on the cloud is extremely time- and cost-intensive. However, edge computing makes it easier to implement cloud services with low latency, high bandwidth, and low jitter. The cloud platform can be a tremendous tool for the smart factory to process massive data. For instance, it provides a scientific basis for production scheduling and market demand forecast. The framework of cloud computing can be used to dispatch and distribute edge computing nodes according to global operational requirements, to equip IIoT nodes with edge decision capabilities. Meanwhile, the task of the edge computing nodes is to provide local data storage. In the case of connection failures to the cloud (e.g., power failure), the data can temporarily be cached at the edge. Once the connection is restored, the locally stored data is optimized and automatically synchronized with the cloud, which ensures full mapping of the equipment.

A Case Study: Active Maintenance

Edge computing can bring significant advantages in terms of efficiency and cost reduction in Industry 4.0. In fact, activities such as active maintenance are being migrated to the network edge to create novel industrial applications, which are changing the service mode. In the case study, we build distributed data processing in the cloud using Hadoop architecture. The Hadoop Distributed File System (HDFS) and Hadoop MapReduce were used to perform realtime data analysis and data mining of the local database. The big data consisted of machine status data and machine log data. All the data is combined to generate a reasoning model, which is loaded on a local Linux system of a Raspberry Pi. An OPC UA server on Raspberry Pi is applied to vendor-neutral transmission of pre-processing information, or raw data from a programmable logic controller (PLC) with safety and reliability. A semantic model is also built to integrate multiple data sources to produce more consistent, accurate, and useful information. This data fusion technology is used to input the acquired data feature to the reasoning model.

In our laboratory, a variety of customized candy products are packed in the production line. Customer order service is provided using a private cloud. An ad hoc network between the edge computing nodes is implemented to realize high-speed and stable communication. The integra-

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tion of the Ethernet with DDS standard protocol is deployed to achieve efficient information interaction. As shown in Fig. 5, the robots get candy packing tasks associated with the cloud, then suck the selected candy and put it into the not packed candy box. During the operation, the robots are represented as network nodes in the backbone network. If any node is overloaded or fails, the task of that node will be switched to an adjacent node. Therein, a multi-agent system is introduced to enhance the autonomous negotiation capability in the smart factory. In this way, each robot can be regarded as an agent. The activities of an agent are autonomous and independent. Their own goals and actions are not restricted by others. The multi-agent system is employed to complete the production tasks with the task procedures assigned to different agents, and we introduce Contract Net Protocol (CNP) [15] to allocate each task through the open tender, bidding, and winning modes. The agents negotiate and resolve the conflicts by means of competition and consultation. Thus, the order task completed in the self-organized task mechanism. On the contrary, the instructions to a subordinate robot are distributed by the central server. This may lead to execution delay and network congestion by the centralized task scheduling mechanism. In this way, the cloud platform actually does not apply in this case. The comparisons between the self-organized task mechanism and the centralized task scheduling mechanism are presented as follows.

For a given order quantity, we compared the operating time between the self-organized task mechanism and the centralized task scheduling mechanism. As shown in Fig. 6a, for an increase in the order quantity, the experimental results show that the self-organized task mechanism based on edge computing is more agile and efficient, especially after 2000 orders. Additionally, as shown in Fig. 6b, we used an Internet speed meter to compare the bandwidth of the core network for the two mechanisms. When the production line was stable, the speed of the production line backbone network based on the centralized task scheduling mechanism was 16~17 Mb/s. Once the Raspberry Pi devices were deployed, the speed of the backbone network based on the self-organized task scheduling mechanism was between 5~6 Mb/s. This showed an overall 60 percent reduction in network speed. The proposed self-organized task scheduling mechanism focuses on the dynamic scheduling problem for IoT-based manufacturing. In this case study, Raspberry Pi as the edge computing node has enough processing ability for data fusion and cooperation with working partners. Cloud services can be transferred to the network edge. The service delay is reduced, and the transmission of large amounts of data is avoided. This is the device domain and data domain application of edge computing in the reference architecture. Furthermore, edge computing will play an important role in IoT-based manufacturing, such as thermal sensors, SDN, and network security.

Conclusions

Edge computing is a new computing paradigm that allows the integration of core capabilities such as network, computing, and storage closer to the peripheral equipment. The application of edge computing in IIoT meets the requirements of real time for lightweight intelligent manufacturing, and increases the agility and security of the network. This article presents a system architecture for implementing edge computing in IIoT applications. The role of edge computing for IoT-based manufacturing is analyzed. The final experiments show that the self-organized task scheduling mechanism with edge computing provides obvious advantages in terms of business agility and bandwidth optimization compared to traditional approaches. Furthermore, as the computational capabilities in the cloud do not include increased response latency or network security, even limited computing resources deployed at the network edge will help in the service quality of industrial use cases in IoT-based manufacturing.

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