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A Smart Manufacturing Service System Based on Edge Computing, Fog Computing, and Cloud Computing

QINGLIN QI AND FEI TAO, (Senior Member, IEEE)
School of Automation Science and Electrical Engineering, Beihang University, Beijing 100083, China

Corresponding author: Fei Tao (ftao@buaa.edu.cn)

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ABSTRACT The state-of-the-art technologies in new generation information technologies (New IT) greatly stimulate the development of smart manufacturing. In a smart manufacturing environment, more and more devices would be connected to the Internet so that a large volume of data can be obtained during all phases of the product lifecycle. Cloud-based smart manufacturing paradigm facilitates a new variety of applications and services to analyze a large volume of data and enable large-scale manufacturing collaboration. However, different factors, such as the network unavailability, overfull bandwidth, and latency time, restrict its availability for high-speed and low-latency real-time applications. Fog computing and edge computing extended the compute, storage, and networking capabilities of the cloud to the edge, which will respond to the above-mentioned issues. Based on cloud computing, fog computing, and edge computing, in this paper, a hierarchy reference architecture is introduced for smart manufacturing. The architecture is expected to be applied in the digital twin shop floor, which opens a bright perspective of new applications within the field of manufacturing.

INDEX TERMS Cloud computing, digital twin, edge computing, fog computing, hierarchical architecture, smart manufacturing.

I. INTRODUCTION

The increasingly evolvement of new generation information technologies (New IT), including cloud computing (CC), Internet of Things (IoT), big data analytics (BDA), artificial intelligence, cyber-physical system (CPS), etc., contributes significantly in manufacturing to achieve more efficient, competitive, and smarter manufacturing [1]. Driven by New IT, smart manufacturing pursues a higher degree of intelligence with the powers of low-cost and ubiquitous sensing, advance computing and data analytics, and cyber-physical integration. The convergence of various advanced and connected devices and machines is the inevitability for smart manufacturing. Moreover, the growing ubiquity of IoT [2], provides promising opportunities to build powerful industrial systems and applications [3]. As a result, a large volume of various manufacturing data is generated by these connected machines and sensors, etc. These data need to be cleaned, stored, and processed to produce information and knowledge, which are poised to be the basis for smart manufacturing [4]. However, the exponential growth of data goes beyond general processing capabilities of users.

Cloud computing is an answer to the extensive need to deal with data explosion in many cases [5]. Cloud computing is an Internet-based computing where the shared resources (e.g., storage and computing facilities, software, data, applications, etc.) are accessed and used on demand in a convenient ''pay-as-you-go'' manner [6]. In the cloud computing paradigm, users get high quality of services at a lower cost. Due to the potential and practical benefits to society and economy, cloud computing paradigm has attracted enormous attention from academia and industry. For instance, a lot of companies, such as Amazon, Google, Salesforce, IBM, and Microsoft etc., have developed their cloud computing platforms to provide services for ubiquitous users [7]. Meanwhile, combined with manufacturing,

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cloud computing gave rise to a new cloud-based manufacturing model. All manufacturing resources and capabilities (MRs&Cs) are virtualized and encapsulated as services to be managed, allocated, and on-demand used through cloud [8], [9]. Bringing together IoT, CPS, BDA, and CC technologies, it enables smart manufacturing [10]. Moreover, cloud computing is also applied in industrial Internet of Things (IIoT) and CPS. For example, Silva *et al.* [11] proposed a cloud-based architecture for IIoT for remote monitor and control industrial devices. Xiong *et al.* [12] designed a cloud operating system for industrial applications. However, data collected from machines and sensors are sent to the cloud and desired output is sent to the desire devices again, which may result in delayed response. Furthermore, massive data requires high bandwidth, which is expensive [13]. With network unavailability, these problems become barriers to applications required delay constraints [14].

Fog computing and edge computing are solutions to above problems, in which some compute, storage, and networking capabilities of cloud are shifted to the edge network [15]. Through fog computing and edge computing, some data from smart machines or sensors do not have to be stored and processed on cloud, but on edge devices instead (e.g., fog routers or smart gateway/IIhub [16], etc.), which fulfills the requirements like low latency, real time response, reduction of network traffic, etc. [17]. Moreover, fog computing is also adept in filtering raw data and reducing resource wastage [18]. As the new paradigm of computing, fog computing and edge computing offer the possibility to increase efficiencies and develop innovative services [5], which would accelerate development of smart manufacturing. Therefore, a reference architecture for smart manufacturing based on edge computing, fog computing and cloud computing, is proposed to provide guidance for the development of smart manufacturing. The reference architecture will be applied in digital twin shop floor to improve different levels of intelligence of shop floor.

The main contributions of this paper include:

(1) The manufacturing system under cloud environment and its general architecture are reviewed, and some problems are summarized.

(2) A hierarchy reference architecture for smart manufacturing based on edge computing, fog computing and cloud computing is proposed to facilitate a new variety of applications and services.

(3) The hierarchical architecture could be applied in the digital twin shop-floor, which opens a bright perspective for smart manufacturing.

The rest of this paper is organized as follows. The solutions of manufacturing system under cloud environment are reviewed in Section II, and their merits and demerits are discussed. In Section III, the reference architecture for smart manufacturing based edge, fog, and cloud computing is presented. In Section IV, applications of the reference architecture in digital twin shop floor is discussed. Conclusion is drawn in Section V.

II. MANUFACTURING SYSTEM ARCHITECTURE UNDER CLOUD ENVIRONMENT AND ITS SHORTAGES

The deep integration of all aspects of the manufacturing process with the New IT, promotes profound changes in manufacturing pattern, which can be named as smart manufacturing [1]. Benefited from New IT, more and more manufacturing devices are connected to the Internet, and more and more users participate in the manufacturing process. As a result, manufacturing system becomes increasingly complex and dynamic, which requires resources and users collaboration. Besides, data generated in manufacturing is also becomes increasingly richer, more diverse and complex. With the powerful computing, high scalability and virtual resource services, cloud provides an efficient manner for massive data processing and storage, and satisfies the demand for large-scale collaboration [19].

A. CLOUD-BASED MANUFACTURING SYSTEM ARCHITECTURE

As one of the major enablers for the manufacturing, cloud computing transformed traditional manufacturing models to computing and service-oriented manufacturing model, which is becoming more interoperable, smart, adaptable and distributed. Besides, IIoT and CPS are also integrated with cloud computing to cope with the challenges with regards to massive data processing, service provisioning, and knowledge management, etc. [20], [21].

From multiple cloud-based manufacturing applications [21]–[25], the cloud-based manufacturing system architecture can be summarized as shown in Figure 1. The architecture consists of two main layers, which are physical manufacturing system and cloud environment. The lower layer represents the MRs&Cs, including manufacturing devices, as well as the users who participate in the manufacturing activities. The physical manufacturing system covers all physical devices on the factory [22], even multiple plants, including cooperative plants located in different regions [23], as well as all users, including enterprise users and customer

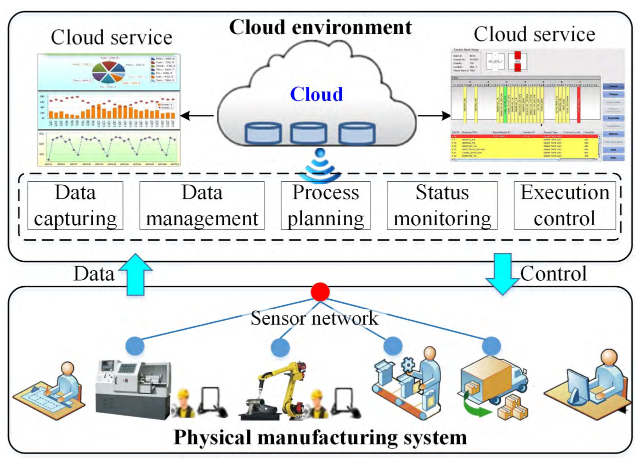

FIGURE 1. The cloud-based manufacturing system architecture.

users [24]. Whereas the upper layer represents data processing, process control and services management in the cloud environment. The cloud provides non-physical services and applications for users in the manufacturing lifecycle. The applications and services provided by cloud are richer, as well as faster, simpler and cheaper to be used. In the manufacturing system under cloud environment, manufacturing enterprises or users do not have to invest in expensive manufacturing resources, but buy manufacturing capacities through the cloud platform in a ''pay-as-you-go'' manner [26]. Cloud connects massive social manufacturing resources together and can provide various manufacturing services, enabling open collaboration and sharing [27].

In this architecture, cloud connects all the manufacturers and customers. Customers communicate with each other and manufacturers to effectively integrate social demands and production capacities by using the desktops or mobile devices [21]. The physical manufacturing system with the MRs&Cs, are sensed and accessed to the cloud by IoT (e.g., smart things, sensor networks, radio frequency identification (RFID), etc.). Each manufacturing unit can be considered as a CPS. Multiple unit-level CPSs constitute the system-level CPS. The integration between the physical devices, users and cloud is enabled by encapsulating data and functions inside services. Moreover, data which are collected from physical manufacturing system, as well as control instructions (e.g., machining parameters, tool path, etc.) [25] from cloud, are transmitted between the lower and upper layers through network. Through the cloud-based solutions, manufacturing enterprises are able to develop better-integrated and more efficient processes with the lower cost.

B. PROBLEMS AND SHORTAGES

The manufacturing system under cloud environment allows higher utilization without increasing investment and degrading performance, as well as frees manufacturers and users from many details. However, there are still many problems that limit the expansion of smart manufacturing.

1) **Overfull bandwidth.** Data generated by various manufacturing resources, which may be geographically distributed, are experiencing explosive growth. These data are conveyed over the network to cloud, where data processing is carried out [28]. The increasing volume and velocity of data require high bandwidth, which is very expensive. When the network congestion is serious, some data may be loss.
2) **Unavailability.** Although the data stored in the cloud can be accessed from anywhere at any time, user relies heavily on the availability of internet connection and the servers [29]. When data cannot be accessed due to the network unavailability, the power of the cloud becomes unusable.
3) **Latency.** Some real-time and concurrent scenarios require time synchronization, bringing real-time issues [30]. The data transmission between terminals and cloud may suffer unacceptable Internet round-trip latency, ranging from tens to a few hundreds of milliseconds [31].
4) **Data validity.** A lot of insignificant data (e.g., redundancy, noise, temporary data, etc.) are conveyed to cloud, which waste resources. Besides, some locally consumed data, also do not need to be sent to the cloud [32]. However, data filtering capacity has not received enough attention.
5) **Security and privacy.** The constant development of new attack vectors (e.g., coming from the communication channels, denial-of-service (DoS) attacks, etc.) results in numerous security issues [33]. Besides, when all the data are conveyed to the cloud, they also contain privacy data, which increases the risk of disclosing user privacy [34].
6) **Inefficient interaction.** The cloud-based communication among manufacturers, users and machines, which may locate in the same area, limits the flexibility and efficiency in connectivity and interactive messaging.

As a result, despite the broad utilization of cloud computing in smart manufacturing, some applications demand real-time sensitive, and precise reaction to events, cannot count on the cloud alone, due to inherent problems [30]. Taking the actual status of smart manufacturing into consideration, some new technical concepts are expected.

III. A REFERENCE ARCHITECTURE FOR SMART MANUFACTURING SYSTEM BASED ON EDGE COMPUTING, FOG COMPUTING and CLOUD COMPUTING

A. FROM CLOUD COMPUTING TO FOG AND EDGE COMPUTING

Cloud computing is the computing paradigm that enables ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., computing and storage facilities, applications, services, etc.) [35]. Through virtualization technology, cloud computing shields the diversity of underlying devices and provides users with a variety of services in a transparent way, including IaaS (Infrastructure-as-a-Service), PaaS (Platform-as-a-Service) and SaaS (Software-as-a-Service) [36]. Due to the increasing number of access devices, cloud computing may face some problems in the bandwidth, latency, network unavailability, security and privacy, etc. Fog computing is considered as an extension of cloud computing to the edge network, providing services (e.g., compute, storage, networking, etc.) closer to near-user devices (e.g., network routers, various information systems, etc.), instead of sending data to cloud [37]. In fog computing paradigm, data storage and processing rely more on local devices, rather than on cloud data center. Fog computing makes the applications more convenient, meeting a wider range of node access. Similar to fog computing, edge computing also allows computation to be performed at the edge of the network, but at closer proximity to the data sources [38]. The difference between fog computing and edge

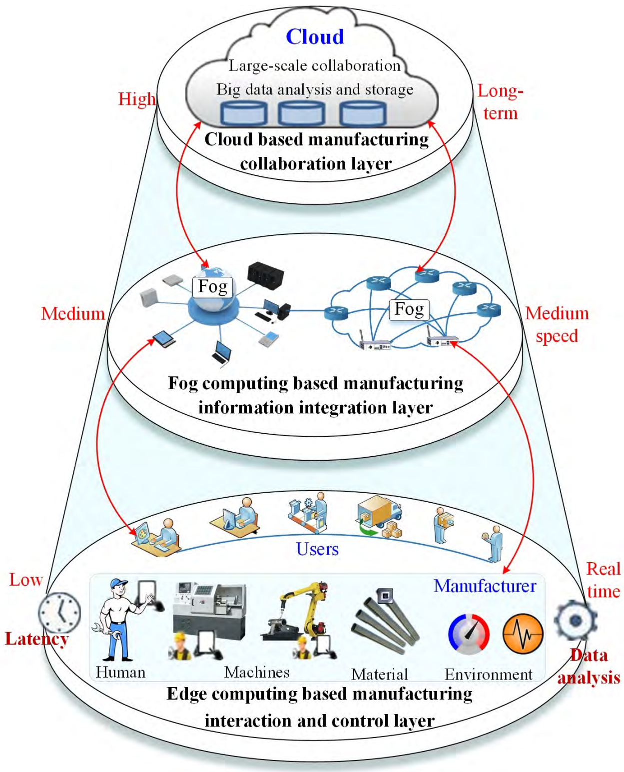

FIGURE 2. **The hierarchy architecture for smart manufacturing based on edge computing, fog computing and cloud computing.**

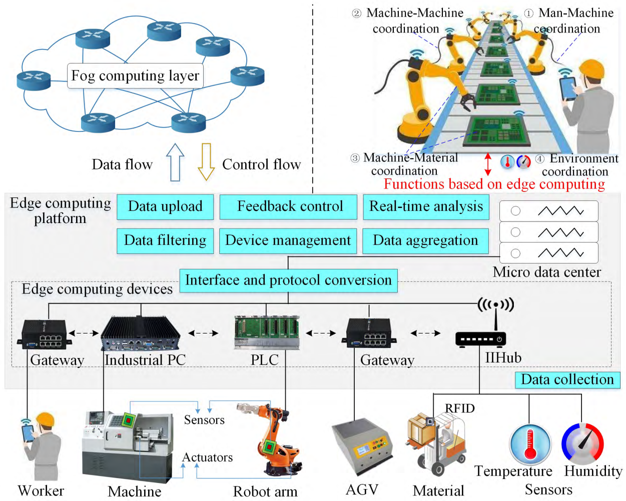

FIGURE 3. **Edge computing based manufacturing interaction and control.**

computing is that fog computing relies on interconnection capabilities among nodes, whereas edge computing runs in isolated edge nodes. Edge computing provides edge services near the source of data to meet the critical requirements in agile connectivity, real-time optimization, smart applications, security and privacy. As the supplementary, fog computing and edge computing, which provide compute, storage, and networking services between end devices and traditional cloud computing [37], offer bright prospects for smart manufacturing applications.

To extend the smart manufacturing applications under cloud environment and offer perspectives for implementation of solutions that require very low and predictable latency, a reference architecture based on edge computing, fog computing and cloud computing for smart manufacturing is proposed. As illustrated in Figure 2, the reference architecture consists of the following three layers.

B. EDGE COMPUTING BASED MANUFACTURING INTERACTION AND CONTROL LAYER

As illustrated in Figure 3, this layer consists of all the manufacturing resources involved in various manufacturing activities. In a shop-floor or factory, principal resources can be summarized as ''Human-Machine-Material-Environment''. Human refers to workers and managers. Machine includes machining equipment (e.g., machine tools, robots, etc.), transporting equipment (e.g., the material conveyors, automatic guided vehicles, etc.). Material consists of raw material, parts and components, semi-finished products, finished products, etc. Moreover, to keep abreast of the real-time changes, a great deal of various sensing devices (e.g., various smart sensors, RFID, etc.) are deployed on the manufacturing resources. Together with actuators and drivers, they form the sensing system and execution system. In addition, the environment factors should also be monitored, such as temperature, humidity, pressure, etc. These resources closely cooperate with each other to carry out various manufacturing activities.

In edge layer, CNC machine tools, smart robots, sensors, terminals, and edge connection devices, not only produce data, but also have the capacities of data analysis and processing, which support edge computing and provide near-edge smart services. At the site closest to the physical equipment, the edge layer uses limited hardware resources (e.g., gateway, industrial PC, PLC, IIHub, etc.) to complete data collection, protocol conversion, data filtering, data upload, data storage, data analysis and other operations. First of all, the real-time status (e.g., regular physical quantity, environmental and operating conditions) and various parameter data of the manufacturing resources and users are collected in real time through appropriate access methods, such as RFID, sensors, industrial Ethernet, et al. At the edge level, there are many types of equipment, whose protocols are varied. Therefore, the first-line task of the edge computing devices is interface and protocol conversion to convert different data formats and communication protocols into a unified protocol. Data interaction in edge layer is realized based on the unified protocol. Moreover, for later processing, the collected data is also subjected to noise processing, abnormal data cleaning, if necessary, data compression. The edge devices also have a certain data storage capability (may not large) to store real-time state data, as well as alarms, faults and other information. Moreover, the micro data center is used effectively store the real-time data of the state of the production field. As the volume of data is large, the edge computing devices would overwrite the original data over a certain period of time with new data. To save data transmission cost and bandwidth, only the necessary edge data is uploaded to upper layer. In addition, much of the collected data may not have much value, just reporting ''normal'' conditions. Therefore, before edge data is overwritten, the edge computing devices would filter, discard, or more efficiently reassemble the data for transmission to the fog or cloud for storage and analysis. For the collected real-time data, the edge computing devices can perform simple data processing and analysis. For example, through data analysis for various sensors, edge computing can determine whether the manufacturing equipment state is normal and what action it is performing. In addition, after simple data processing and analysis, automatic feedback control for the operation of the manufacturing equipment according to preset rules can be realized. The feedback control on the edge side is sufficient to ensure real-time performance. Even in the case of offline, edge computing is still able to provide localized application services.

On the basis of realizing the smart perception and interconnection, this layer is to further realize the following functions based on edge computing. 1) Man-Machine coordination. Through integrating the accuracy of machine and the flexibility of human, manufacturing system can be quickly adjusted to adapt to the dynamic production activities. As a result, human and machines can be harmonious coexistence. 2) Machine-Machine coordination. The machines cooperate with each other, which could effectively improve the speed and efficiency. Through machine-machine collaboration, manufacturing system could have better robustness and the self-regulating capacity. As a result, manufacturing would be more flexible, so as to produce diversified products more efficiently. 3) Machine-Material coordination. Based on sensors, RFID, machine vision, etc., material and products can be sensed and positioned intelligently. In the light of the edge computing, smart machines automatically execute the corresponding machining program. 4) Environment coordination. The manufacturing environment is dynamically changed to ensure product quality and equipment safety according to the specific requirements.

C. FOG COMPUTING BASED MANUFACTURING INFORMATION INTEGRATION LAYER

This layer is responsible for medium speed and latency data analysis for manufacturing information integration and management. The components (e.g., network routers, regional servers, network switches, etc.) of edge or core network, and enterprise-class management systems could be used as the infrastructures for fog computing. These infrastructures can provide different compute, storage, and networking functions. Through fog computing, multiple applications and services deployed at this layer can connect a large number of smart equipment and sensors, and integrate the data from them.

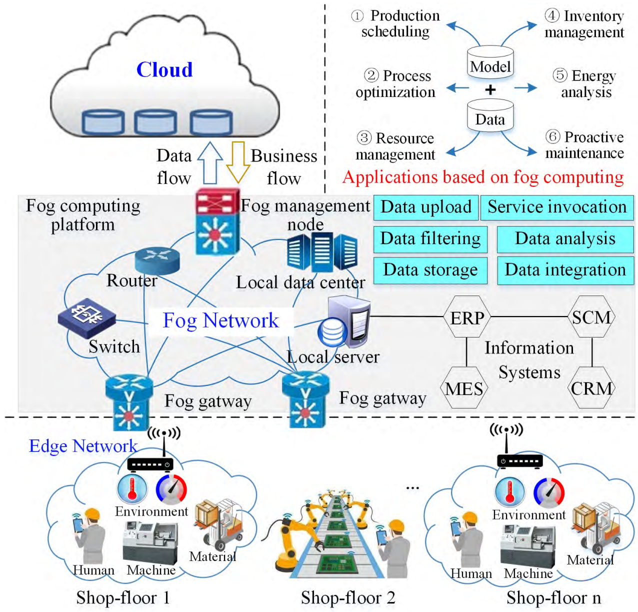

FIGURE 4. Fog computing based manufacturing information integration.

As shown in Figure 4, the fog layer is a network group composed of interconnected fog nodes. Each fog network has a fog gateway and a fog management node, as well as inner fog nodes (e.g., router, network switch, local sever, local data center, etc.). The functions of the fog gateway are to support edge network access, receive data collected at the edge layer, and perform further processing. The fog management node can be aware of all the fog nodes in a fog network. The fog node communicates with the cloud data center of the external network through the fog management node. In fog layer, edge connection devices and edge computing devices communicates with the fog gateway through a single-hop low-latency link. The inner fog nodes communicate with the edge layer through the fog gateway. The main function of the inner fog node is to perform data processing (data filtering, compression, storage, encryption, etc.) on the data from the edge layer and processing service requests. When a inner fog node receives the task request assigned by the fog management node, it can perform the task locally, or may send the data to other fog nodes to compute. The fog management node is responsible for the coordinated assignment of task requests and computing resources within the fog. Under the unified management of the fog management node, the fog layer achieves mutual cooperation between the fog nodes. In the fog layer, data from different edge networks is further unified, including data formats and communication protocols. Then these data are integrated to find valuable insights for enterprise-level applications. The fog nodes can effectively reduce the service delay and the amount of data transmitted in the network. Finally, part of the data in fog layer is transmitted to the cloud computing layer, to drive the corresponding services.

On the basis of information integration, this layer could achieve some management applications, such as inventory management and process optimization, etc. These applications need to get insights from the integrated data. With respect to inventory management, the volume and batch of material consumed in manufacturing activities, as well as different kinds and quantity of finished products are continually recorded. As a result, the managers are able to keep abreast of inventory changes of material and products. As for the process optimization, the historical process data is analyzed in this layer. The correlation between different technological parameters and the effect of these parameters on yield and quality can be determined by analyzing the process data. The productivity and product quality can be improved effectively by adjusting technological processes in relation to these parameters.

On the other hand, this layer also receives the data from outside enterprise (such as orders, invoked services, etc.), which are mainly from the cloud. Based on these data, manufacturing companies carry out production planning and resources scheduling, etc. For instance, once the manufacturing enterprise receives the orders from customers, production plans are developed to determine the optimal configuration of manufacturing resources according to the availability of resources. In addition, when some faults occurred, the managers contact third-party maintenance serviceman to replace or repair the malfunction equipment. As an intermediate layer, fog computing paradigm reduce bandwidth towards the cloud, and provide computing and storage services for the enterprise management applications. Moreover, the data form manufacturing resources is further filtered in this layer to be forwarded to cloud.

D. CLOUD COMPUTING BASED MANUFACTURING SERVICE COLLABORATION LAYER

The diversification of market and customer demands, requires manufacturing enterprises to have abilities to manufacture multiple products. Moreover, with the continuous improvement of product performance and structure, it is impossible to complete all the manufacturing activities only by a single enterprise. Therefore, socialized sharing of MRs&Cs, enterprise and business collaboration, as well as the socialized user participation, become an inevitable trend. To achieve better sharing of limited resources and efficient value-adding, manufacturers should make full use of high-quality resources in the whole society to conduct large-scale collaboration in product design, manufacturing, marketing and services. With the characteristics of ubiquitous, convenient, on-demand resources sharing, low costs and interoperability, cloud pave the way for the large-scale collaboration. In this layer, all the MRs&Cs are managed in the form of cloud services to be shared by various users, including the resources services, data services, models services, knowledge services, etc. Through services, various MRs&Cs would become ‘‘plug-and-play’’ components. In addition, not only providers could conveniently provide their services to their collaborative stakeholders, but also manufacturing enterprises could use various resources in a pay-as-you-go manner. As a result, different kinds of collaboration applications, such as commerce cooperation, manufacturing cooperation, business cooperation, are achieved, greatly improving the value and efficiency of enterprises. Besides, various users could also participate in the innovation of product and value creation with the help of cloud services.

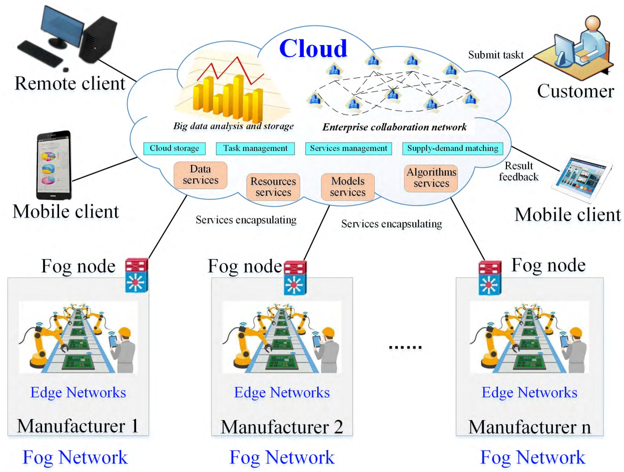

FIGURE 5. Cloud based manufacturing collaboration.

In addition, as shown in Figure 5, cloud layer is responsible for big data analysis and storage. In the process of manufacturing activities and enterprises collaboration, a large volume of data is generated. With powerful computing and storage capabilities, cloud layer receives and processes massive data uploaded by fog management node from the fog layer and edge layer. In order to extract additional value from data, data processing models are established to analyze large computational complexity, low latency sensitivity and massive data, and display the results. Taking the fault diagnosis of equipment as an example, diagnostic model is established based on equipment data. The larger the amount of equipment data, the easier it is to form an accurate and reliable diagnostic model, which requires more computing resources and higher computing power. So the diagnostic model is more suitable for forming and updating in the cloud. After the diagnosis model is formed, the model is downloaded to fog layer and edge layer to realize real-time and reliable equipment diagnosis. Therefore, big data analysis and mining are performed in cloud layer to form a model. The fog layer and edge layer download the model to perform real-time analysis on the real-time status. During the equipment running process, new data is generated and uploaded to cloud again. The model in cloud layer will be updated based on historical big data and new data. Besides, big data provides sharper insight for businesses, such as market trends analysis, risk assessment, etc.

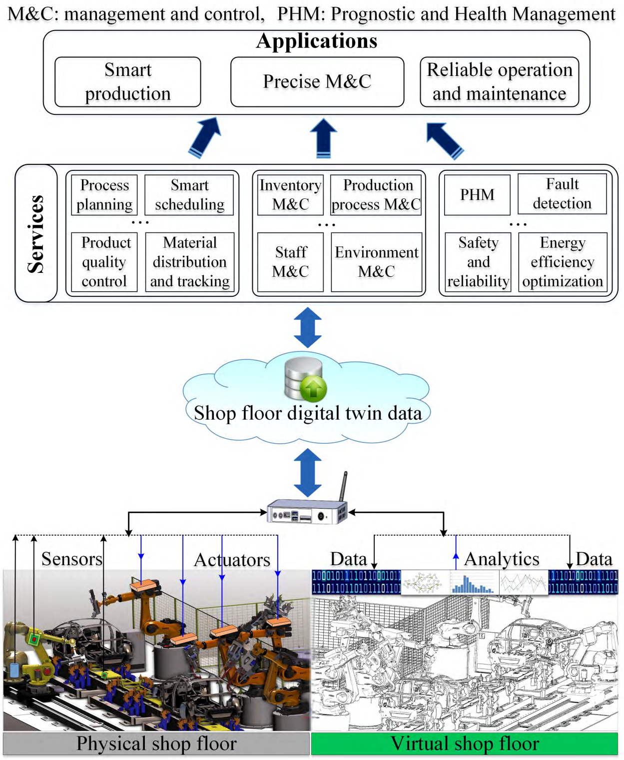

FIGURE 6. Digital twin shop-floor (DTS) framework [40].

TABLE 1. Services in various layer.

Edge services	Fog services	Cloud services
Data sensing	Data acquisition	Virtualization
Data cleaning	Data reduction	Data integration
Edge storage	Fog storage	Cloud storage
Edge analysis	Fog analysis	Big data analysis
Iterative interaction	Asset optimization	Task management
Simulation	Process planning	Supply-demand matching
Real-time monitoring	Proactive MRO	Personalized customization
Disturbance found	Smart scheduling	Smart design collaboration
Real-time control	Precise management	Supply chain collaboration
Material racking	Material distribution	Commerce collaboration

IV. PERSPECTIVE FOR APPLICATION OF THE REFERENCE ARCHITECTURE IN DIGITAL TWIN SHOP-FLOOR

As an effective way for cyber-physical integration, digital twin provides manufacturing enterprises with a new way to carry out smart production and precision management [39]. Digital twin shop-floor (DTS), as a basic unit of smart manufacturing, would become imperative. The hierarchical data processing structure of above architecture could be tremendously beneficial to DTS. The DTS and services in various layers are shown in Figure 6 and Table 1.

As shown in Figure 6, DTS consists of four components, which are physical shop-floor (PS), virtual shop-floor (VS), shop-floor digital twin data (SDTD), and service systems (Ss) [40]. PS includes a series of physical manufacturing resources, i.e., ''Human-Machine-Material-Environment''. VS is a collection of various multiple-dimensional models, which are the faithful mapping of PS. Ss provide system support and services for DTS. Data from PS, VS and SS are integrated and fused in SDTD. Through the ultra-high-fidelity mapping and real-time interaction among PS, VS, Ss and SDTD, the production elements management, production planning, production process control in DTS are optimized.

As shown in Figure 7, the cloud services system is based on cloud computing, which connects users and the manufacturing shop-floor. Users submit their personalized product requirements as tasks to the cloud platform. Through task management, a complex product task is decomposed into sub-tasks that can be accomplished by a single service. According to the QoS, the manufacturing service supply-demand matching and scheduling is carried out to select optimal services. Through service combination and collaboration, selected services from different enterprises are invoked and combined to complete the task collaboratively. As a result, personalized customization, smart design, and supply chain collaboration, etc., are achieved. In addition, the MRs&Cs services from DTS constantly update their status based on the data from physical resources and virtual models, and participate in the services collaboration. Once the services from DTS are invoked, specific requirements would be conveyed to enterprise or shop-floor management systems.

The management systems are based on fog computing, which is responsible for precise M&C, and reliable operation and maintenance. The management systems constantly acquire the status data of the physical resources, i.e., ''Human-Machine-Material-Environment'' in the PS, to analyze, evaluate and predict the availability and performance of PS. For instance, through analyzing the historical and real-time status data of machines by statistic method, mathematical modeling, and machine learning, etc., the prediction models are built. According to the prediction models, the health conditions of machines or their components, the tendency for machines capacities to deteriorate, and the lifespan of components could be quantified and visualized. Moreover, when the order is received, taking the costs, resources performance, completion time, production efficiency and other constraints into consideration, production plan is developed. By determining the machining equipment, organization mode, processing sequence of the workpieces, as well as the allocation scheme of material, work in process (WIP) and other key resources in the premise of satisfying imperative constraints, management systems could optimize the performance of the shop-floor. Fog computing provides storage, compute, analysis, and network support for data processing of management applications, such as resources management, energy management, proactive MRO, etc.

The real-time iterative optimization of shop-floor is based edge computing. Due to the collaboration of human, machines, material, environment and other heterogeneous elements, as well as the uncontrollability of the emergency, it is likely to cause downtime, delay and other phenomena.

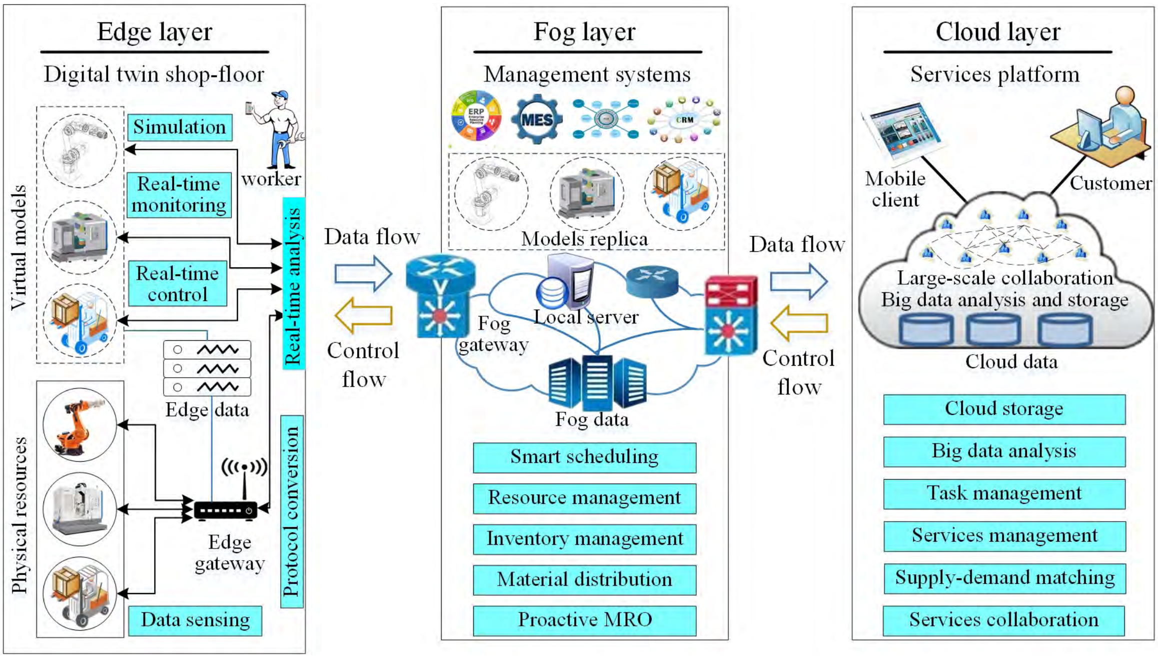

FIGURE 7. Digital twin shop-floor based on edge computing, fog computing and cloud computing.

They may reduce resources utilization, increase the additional inventory and energy costs, and other penalties. Therefore, physical resources and virtual models interact and cooperate with each other to optimize the production process. Above of all, physical resources and virtual models receive the operation instructions from management systems in accord with production plan, to organize production. Then, in the actual production process, the physical resources would transmit the real-time data to the virtual models. The virtual models evolve according to the real-time state of the physical resources, and identify the production schedule and disturbance factors. Coping with the disturbance, virtual models are to optimize the production process from the perspective of all elements, whole process, and whole businesses, based on real-time and historical production data. According to the simulation of virtual models, the physical resources are adjusted and controlled in real time, achieving optimal production. Edge computing shields the heterogeneity of physical interfaces and communication protocols, facilitating the real-time interaction of physical resources and virtual models. Besides, the high speed and low latency real-time data analysis of edge computing enables the optimal control.

The data from PS, VS, and SS are stored and processed through edge computing, fog computing and cloud computing according different time-sensitive. Through the data cleaning, reduction, modeling, association, clustering, integration, evolution, fusion and other operations in various layer, the fused SDTD reflect the dynamic evolution process, evolution laws, and statistical characteristics of DTS.

V. CONCLUSION

Smart manufacturing system involves multiple levels. The underlying layer is the smart devices, which are the sources of data and provide edge computing. The middle layer is the data transmission network, in which fog computing is carried out. The top layer is the cloud, in which big data is stored and analyzed. Through the computing, storage, and networking capabilities in the near-end nodes, edge computing and fog computing reduce the data sent to cloud, and the probabilities of service downtime, ensuring the robustness of smart manufacturing system. Edge computing, fog computing and cloud computing cooperate with each other, better meeting the requirements of smart manufacturing applications.

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QINGLIN QI received the B.S. degree in computer science and technology from the Ocean University of China, Qingdao, China, in 2012, and the M.S. degree in computer science and technology from Beihang University, Bejing, China, in 2015, where he is currently pursuing the Ph.D. degree.

His research interests include service oriented smart manufacturing, manufacturing service management, and digital twin.

FEI TAO received the B.S. and Ph.D. degrees in mechanical engineering from the Wuhan University of Technology, in 2003 and 2008, respectively.

He is currently a Professor with the School of Automation Science and Electrical Engineering, Beihang University, Beijing, China. His current research interests include service-oriented smart manufacturing, manufacturing service management, sustainable manufacturing, and digital twin driven product design/manufacturing/service. He has authored five monographs and over 100 journal papers in these fields.