IoT-Based Intelligent Perception and Access of Manufacturing Resource Toward Cloud Manufacturing

Fei Tao, *Member*, *IEEE*, Ying Zuo, Li Da Xu, *Senior Member*, *IEEE*, and Lin Zhang, *Senior Member*, *IEEE*

***Abstract*—Recently, cloud manufacturing (CMfg) as a new service-oriented manufacturing mode has been paid wide attention around the world. However, one of the key technologies for implementing CMfg is how to realize manufacturing resource intelligent perception and access. In order to achieve intelligent perception and access of various manufacturing resources, the applications of IoT technologies in CMfg has been investigated in this paper. The classification of manufacturing resources and services, as well as their relationships, are presented. A five-layered structure (i.e., resource layer, perception layer, network layer, service layer, and application layer) resource intelligent perception and access system based on IoT is designed and presented. The key technologies for intelligent perception and access of various resources (i.e., hard manufacturing resources, computational resources, and intellectual resources) in CMfg are described. A prototype application system is developed to valid the proposed method.**

***Index Terms*—Access, cloud manufacturing (CMfg), intelligent perception, Internet of Things (IoT), manufacturing resource, manufacturing service.**

I. Introduction

IN order to achieve full-scale sharing, free circulation and transaction, and on-demand-use of manufacturing resources and capabilities, the information technologies [such as network technology, service-oriented architecture (SOA), communication technologies, etc.] have been widely used in manufacturing and industry during the past thirty years. A lot of enterprise information technology and advanced manufacturing systems (AMSs) or modes have been proposed such as application service provider (ASP) [1]–[5], virtual manufacturing (VM) [6], global manufacturing (GM) [7], [8], manufacturing grid (MGrid) [9]–[14], intelligent manufacturing (IM) [15], [16], agile manufacturing (AM) [17], [18], industrial product-service system (IPS^2) [19], [20], cloud manufacturing (CMfg) [21], [23], and so on. Among these AMSs, the CMfg is a computing and service-oriented manufacturing model, which is developed from existing advanced manufacturing models (e.g., ASP, AM, NM, and MGrid) and enterprise information technologies under the support of advanced computing technologies (e.g., grid computing and cloud computing), Internet of Things (IoT), virtualization and service-oriented technologies, and advanced management technologies. Because CMfg could provide cost-effective, flexible, and scalable solutions to manufacturing companies by sharing manufacturing resources and capabilities in the form of services with lower support and maintenance costs [76], it has recently been widely studied by researchers from all over the world [71]–[73], [76]–[80].

The typical research works on CMfg are as follows. The concept, architecture, core enabling technologies, and characteristics of CMfg have been widely studied by members of the CMfg research center from Beihang University in China [21]. A cloud-based design and manufacture (CBDM) model composed of a cloud consumer, cloud provider, cloud broker, and cloud carriers was studied, and a distributed infrastructure with centralized interfacing system as the CBDM architecture was proposed by Wu *et al.* [78] and Schaefer *et al.* [79] from Georgia Institute of Technology in USA. Yip *et al.* [76] from U.K. studied the product configuration for CMfg, and Xu [77] from New Zealand presented some methodologies including such technologies as radio-frequency identification (RFID), wireless sensor networks, and global positioning system (GPS) for identifying distributed resources. Wang [80] from Sweden studied and developed an Internet- and Web-based service-oriented system for machine availability monitoring and process planning toward CMfg. In addition, Tao *et al.* [21] have studied manufacturing resource and service management [67], including the utility modeling, equilibrium and collaboration of manufacturing resource service transaction, and resource service scheduling based on utility evaluation, service composition and its optimal-selection algorithms, service composition network in CMfg system or service-oriented manufacturing systems.

Apparently, before a CMfg model or system has been fully accepted and used by users (including manufacturing service provider, operator, and consumer) and has been successfully and widely applied in manufacturing industry, the profit by using the CMfg system for each side (including manufacturing service provider, operator, and consumer) should be fully considered and guaranteed, especially for the providers and consumers. However, the profits are primarily generated in the providing,

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F. Tao, Y. Zuo, and L. Zhang are with the School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China (e-mail: ftao@buaa.edu.cn).

L. D. Xu is with the Institute of Computing Technology, Chinese Academy of Sciences, Beijing 100864, China; with Shanghai Jiao Tong University, Shanghai, China; with the University of Science and Technology of China, Hefei 200240, China, and also with Old Dominion University, Norfolk, VA 23529 USA.

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consuming, and operating process of various manufacturing services. Therefore, without enough available services, the aim of CMfg cannot be realized. The life cycle of a manufacturing service can be briefly classified into the following three stages: 1) service generation based on the intelligent perception and connection of various manufacturing resources and capabilities; 2) manufacturing service management such as service description, match and search, composition, evaluation, scheduling, transaction, and so on; and 3) service invoking. Obviously, service generation (i.e., how to realize the intelligent perception and connection of manufacturing resources and capabilities) is the foundation and start point in the entire life cycle of manufacturing.

However, few works have been emphasized on the issues of perception, connection, and gathering of manufacturing resources and capabilities, such as the following: 1) intelligent perception of manufacturing resources and capabilities, especially for the physical manufacturing resource; 2) intelligent connection and communication among manufacturing resources, such as manufacturing equipment and machines; and 3) how to generate the manufacturing service, and realize the gathering of various manufacturing services, and so on. It results in the interest of provider is not effectively guaranteed, and many providers do not want to provide and contribute their idle manufacturing resources and capabilities to the CMfg system or platform, or they have no positive motivation to provide high quality and reliable resource services. Consequently, without the adequate and available, high quality and reliable manufacturing services, consumer requirements cannot be met and their tasks cannot be well fulfilled via the CMfg system. Both provider and consumer lose their interest and enthusiasm to use the CMfg system, and the development and wider practice application of the above-mentioned advanced manufacturing modes are hindered. Therefore, more attentions should be paid to the intelligent perception, connection, and access of manufacturing resources and capabilities.

On the other side, a new technology—the Internet of Things (IoT) emerges along with the development of information technology and has been widely used in different fields. It can provide a new approach to the perception and access of CMfg resources. With the support of IoT technologies such as RFID, embedded system, various intelligent sensors (e.g., optical fiber sensor), both the physical hardware manufacturing resource (e.g., manufacturing equipment) and software manuacturing resource (e.g., manufacturing software/application system or tools, and data such as demand information, product structure data information, and process information) can be intelligently preceived and connected to the wider networks. Therefore, the required and useful information and data of these manufacturing resources can be intelligently collected and can used in the entire life cycle of manufacturing, and these resources can be automatically managed and controlled.

Hence, the intelligent perception, connection, and access of various manufacturing resources and capabilities based on IoT are emphasized in this paper. The perception and access method based on IoT for hard manufacturing resources, computational resources, and intellectual resources are investigated. A prototype application system is developed to valid the proposed method.

The remainder of the paper is organized as follows. Section II introduces the current research and application of IoT. The classification and relationship of manufacturing resources and services in CMfg systems are studied in Section III. The architecture of intelligent perception and access of manufacturing resources based on IoT is put forward in Section IV. The technologies of intelligent perception and access of CMfg resources as well as a prototype system are studied in Section V. Section VI summaries the whole paper and points out the future works.

II. IoT and Its Application in Manufacturing

A. Related Research about IoT Technologies

The concept of IoT [24], [25] can be tracked back to the book "The Road Ahead" which is published in 1995. But for the limitations of the wireless network, hardware, and sensor equipment, the IoT has not been paid enough attention at the early time. With the fast development of RFID technology, IoT has been paid more and more attention recently. Because IoT could provide a promising opportunity to build powerful industrial systems and applications by leveraging the growing ubiquity of RFID, wireless, mobile and sensor devices, embedded object logic, object ad hoc networking, and internet-based information infrastructure. Therefore, it has attracted much attention both from the industrial and academic, and many scientific studies have been conducted in this field.

For example, regarding IoT framework or architecture, a preliminary study has been conducted under the support of EU FP7 project (IoT-A and IoT.est); of which IoT-A was proposed to establish a reference modal architecture and define an initial set for the major component modules of IoT, and IoT.est was proposed to establish an effective dynamic services architecture for IoT [26].

Toma *et al.* [27] carried out related studies to integrate various IoT technologies into the same uniformed platform, and analyzed how to use intelligent object framework to encapsulate the RFID, sensor technology, embedded technology, ad hoc network technology, and Internet-based information infrastructure. Atzori *et al.* [28] put forward the concept, architecture, and network characteristics of social IoT by combining the IoT with social networks. After analyzing the basic characteristics of IoT, Ning and Wang [29] pointed out two potential developing trends of IoT architecture, i.e., Unit Internet of Things (Unit IoT) and Ubiquitous Internet of Things (Ubiquitous IoT). At the same time, they pointed out that Unit IoT is similar to human neural network model (MLA), and Ubiquitous IoT is the global IoT or a combination of many single IoTs whose architecture is primarily using the model of social organization foundation (SOF).

In addition, Chalasani and Boppana [30] discussed data architectures for RFID transactions. Jammes and Smit [31] analyzed the problem of optimizing a cost function for wireless sensor networks under energy consumption constraints. Palopoli *et al.* [32] realized scalable offline optimization of industrial wireless sensor networks. Caione *et al.* [33] proposed a new algorithm for in-network compression aiming at longer network lifetime and Henseler *et al.* [34] proposed a novel system architecture and accompanying cryptographic protocols. In addition, RFID as the identification technology of the IoT has also been widely studied and analyzed [35], [36].

B. Applications of IoT in Manufacturing

With the support and application of IoT technology, the potential intelligent and real-time operators of 4C (i.e., perception and Connection, Communication, Computing, and Control) to both physical and virtual objects can be realized, therefore it has a wide range of applications in many fields [37, 38], including aerospace, automotive, communication, medical and healthcare, manufacturing industry, and so on.

For example, in the field of aerospace industry, the application of IoT can effectively improve the product's safety and reliability by identifying the fake and shoddy parts or products. An investigation published by the US aviation declared that at least 28% of air accidents or incidents are caused by counterfeit products [39]. After employing IoT technology to indentify and pick out the unqualified parts/products, production processing, assembling, and so on, the safety and operational reliability of aircrafts have been significantly improved.

In the automotive industry, IoT is widely used in the production line, quality monitor and control, assemble line, logistics and product (or part) tracking, and the real-time link of customer service. Among the procedure, intelligent labels are posted on the components in every part of the link to make it easy to track or invoke, together with the associated attribute information [68], [69], such as the manufacturer's name, serial number, product type, product code, the place and time of the production, as well as the exact location of the product.

In the communication field, the application of IoT makes it possible to integrate the applications of different communication technologies. Before the generation of networking technology, Global System for Mobile Communications (GSM), near-field communication (NFC), low-power Bluetooth, wireless LAN, multi-level network, GPS and sensor network technology [70] are used and applied independently. However, the IoT technologies enable the cross-use of the above-mentioned communication technologies.

Furthermore, the IoT technologies have been widely used for water resource management [43], people with disabilities [40], supply chain [41], [42], [75], in-home health care [44], enterprise information systems [45], life cycle assessment of energy-saving and emission-reduction of products [81], cloud computing [46], and CMfg [82]. Recently, Xu *et al.* [37], [47], [48] have reviewed the advances of IoT in enterprise system and industries. Fan *et al.* [50] studied IoT-based smart rehabilitation system, and Bi *et al.* [49] studied the application of IoT in modern enterprise systems and He *et al.* [51] have researched the application of IoT in the developing of vehicular data cloud service. In addition to employ IoT to identify physical and virtual objects, IoT has also been studied and used for the connection, identification, and communication of such objects in an internet-like structure, such as service composition [52]–[54], database management, and requirement-oriented participation decision and compliance checking in service workflows [55], and so on.

Furthermore, IoT technologies can also be used in many industrial domains, such as design and development of enterprise information systems [56]–[58], [74], data management and processing system [59], energy management and monitoring for public infrastructures and systems [60]–[62], research and development of IT devices and softwares [63]–[66], and so on.

III. Manufacturing Resources and Manufacturing Services in CMfg

A. CMfg Resources and Their Classifications

Manufacturing resources in CMfg system primarily refer to the resource involved in each production action during the entire life cycle of a product, including materialized resources (such as manufacturing equipments, manufacturing cells, product lines, tools, material, products, software, etc.) and the capabilities for resolving a manufacturing problem such as human resource, manufacturing information, etc. There are different kinds of classifications about manufacturing resources according to different aim. For example, according to the two phases of a new product (i.e., the production of the product and after the product is produced), the manufacturing resources can be classified into production-related resource (e.g., raw materials and semi-products, manufacturing equipment, related design and manufacturing software/application system or tools, and datum about demand information, product structure data information, and process information) and product-related resource (e.g., soft and hard resources involved in the process of transportation, sales, maintenance and repair, recycling, and end-of-life treatment of a product).

In this study, for the aim of realizing the intelligent perception, connection, and access of various manufacturing resources and capabilities, the manufacturing resources are divided into four big classifications as shown in Table I: 1) hard manufacturing resources; 2) computational resources; 3) intellectual resources; and 4) other resources. Hard manufacturing resources primarily refer to the manufacturing equipments and materials required in manufacturing activities. Computational resources mainly refer to application system resources, server resources and storage resources. Intellectual resources primarily include human resources with certain knowledge and skills (individual or group), intelligence (knowledge, management, mental and creative, etc.) and technical resources existing as intellectual achievement and intellectual support. The other resources refer to the resources not belonging to hard manufacturing resources, computational resources and intellectual resources.

B. CMfg Services and Their Classifications

The manufacturing services in this study refer to the results of encapsulation and servitization of various manufacturing resources and capabilities. According to the above classifications of manufacturing resources and our research on CMfg, the services involved in CMfg primarily consists of *manufacturing resource service*, *computational resource service* (or *cloud computing service*), and *web services* in this study, which are described in detail as follows.

TABLE I
CLASSIFICATION OF MANUFACTURING RESOURCE [67]

Manufacturing resource classification		Resource description
Hard manufacturing resources (HMR)	Equipment resources (ER)	All kinds of equipment that have certain function required in manufacturing activities.
	Material resources (MR)	Material, semi-manufactured goods, raw and processed materials, fuel, finished-product and so on required in manufacturing activities.
Computational resources (CR)	Application system resources (ASR)	All kinds of software required in manufacturing activities, including design systems, simulation systems, analyzing systems, management systems, and graph processing systems.
	Server resources (SR)	All kinds of servers required in manufacturing activities, such as racks of servers, blade servers, machine cabinet servers, etc.
	Storage resources (STR)	All kinds of memories required in manufacturing activities, such as flash cards, micro hard disk, etc.
Intellectual resources (IR)	Human resources (HR)	The people that has certain ability required in manufacturing activities, such as operation, manage or technique and so on.
	Knowledge resources (KR)	All the knowledge required in manufacturing activities, such as the experience knowledge, models, standards, related documents and other resources.
	Technical resources (TR)	The set of technical resources and condition required in manufacturing activities.
Other resources (OR)	Public service resources (PSR)	Information querying, training, maintenance and so on, provided for resources users.
	User information resources (UIR)	The information that records the basic information about both resources provider and user, such as credit, etc.
	Other basic resources (OBR)	Other resources which are not includes in above-mentioned resources.

1) Computational Resource Service (or Cloud Computing Service): The idea of CMfg is the development and application of cloud computing in manufacturing, hence the computational resources in cloud computing are a main part of CMfg resources. Therefore, the services involved in cloud computing are also included in the CMfg service set, including:

1) *Infrastructure as a service* (IaaS): The infrastructure, such as the storage and compute capabilities required in the entire life cycle of manufacturing, is provided as a service.
2) *Platform as a service* (PaaS): The platform is provided as a service, which can enable the development and deployment of manufacturing applications without the cost and complexity of buying and managing the underlying hardware and software layers.
3) *Software as a service* (SaaS): The application and software are offered as a service, in which the application runs on the cloud, and the needs to install and run the application on the client computer are eliminated.

2) Manufacturing Resource Service: It can be simply defined as a result of encapsulation and servitization of manufacturing resources, especially for the hard manufacturing resources. Compared with cloud computing, in a CMfg system, in addition to the computational resource, there are many manufacturing resources including production-related resources and product-related resources, and logistics-related resources. Accordingly, there primarily are three kinds of manufacturing resource services.

1) Production-related service, which refers to the production-related resources and capabilities are encapsulated and provided as services, including design service, manufacturing service, experimentation service, testing service, simulation service, and so on.
2) Product-related service, which refers to the production-related resources and capabilities are encapsulated and provided as services, including packing service, sale service, maintenance and repair service, recycling service, and end-of-life treatment service.
3) Logistics-related service, which means the logistics-related resources are provided as services.

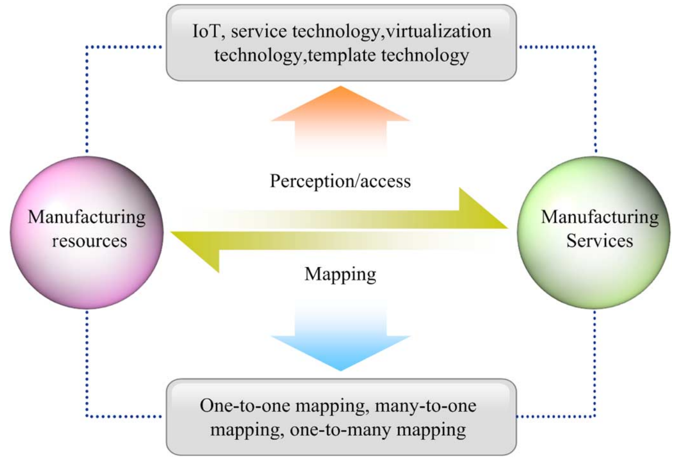


Fig. 1. Relationship between manufacturing resources and manufacturing services in CMfg.

3) Web Services: It refers to the applications or functions (e.g., knowledge service, electronic technical manual, online payment service, online-query, etc.) that required as the auxiliary and supplements to the running of the above-mentioned services, which are primarily provided in the form of service via Internet such as by business web and social web. In other words, it can be treated as a result of encapsulation and servitization of various intellectual resources.

C. The Mapping Relationship Between Manufacturing Resources and Manufacturing Services

As pointed out before, manufacturing services in this study is defined as a result of encapsulation, virtualization, and servitization of various manufacturing resources and capabilities. A manufacturing service can be tread as the digital abstraction and description of the comprehensive information and logic attributes (e.g., functions, capabilities, key parameters, etc.) of the related specific manufacturing resource. Therefore, the mapping relationship between manufacturing resources and service can be classified as follows which is shown in Fig. 1.

1) One-to-One Mapping Relationship: If the function or capability provided by a resource is one and only one, and the function can meet a specific manufacturing requirement, then the servitization result of this resource is only one too, i.e., only one service can be generated. Under this condition, the mapping relationship of the resource and service is "one-to-one." It is the basic mapping relationship between manufacturing resource and service.

2) Many-to-One Mapping Relationship: If a service requirement (e.g., a specific manufacturing requirement) cannot be met

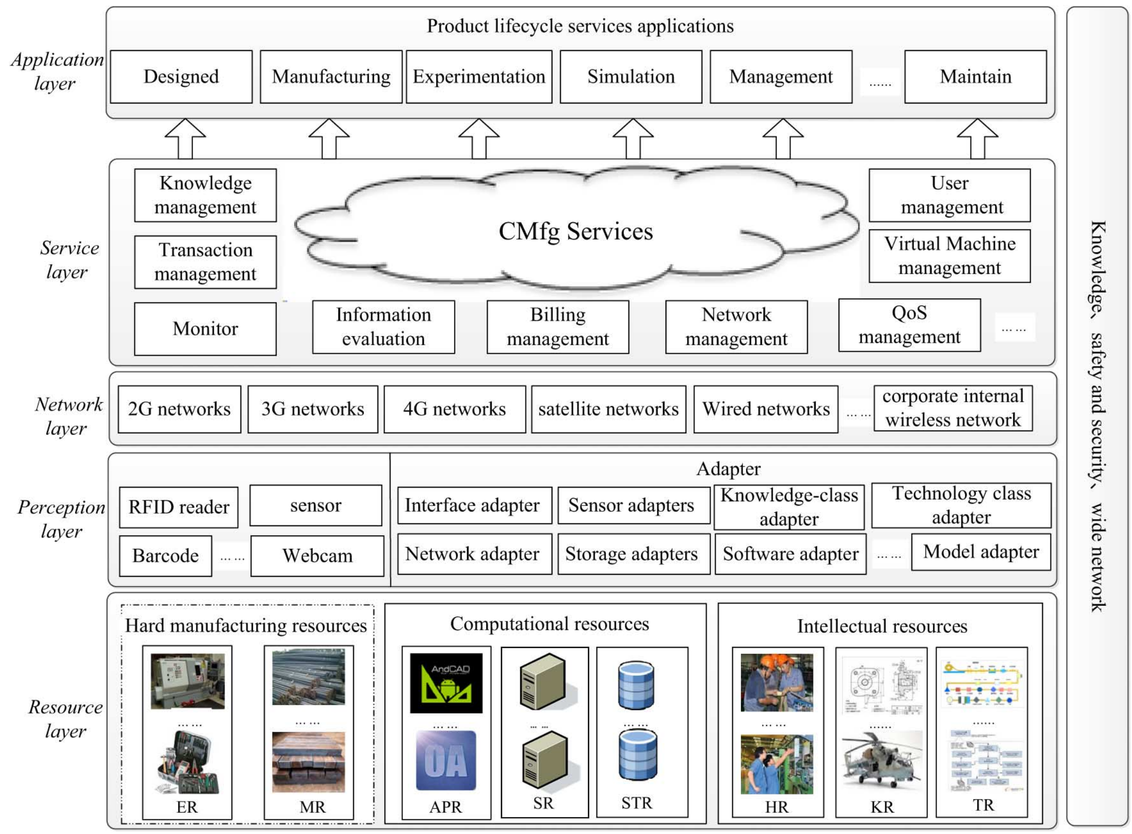


Fig. 2. Architecture of intelligent perception and access of CMfg resources based on IoT.

or satisfied by the function or capability provided by only one resource, but the collaboration or combination of two or many resources, then the required service actually can be seen as the combination of the servitization result of these resources. Under this condition, the mapping relationship of these resources and service is "many-to-one."

3) One-to-Many Mapping Relationship: If the function or capability provided by a resource is *more than* one, and *each one* can meet a specific manufacturing requirement *independently*, then the servitization result of this resource can be several different services, i.e., more than one service can be generated based on the service. Under this condition, the mapping relationship of the resource and service*s* is "one-to-*many.*"

IV. System Architecture of Intelligent Perception and Access of Manufacturing Resources Based on IoT

In order to achieve intelligent perception and access of manufacturing resources, this paper uses the technology of IoT to perceive manufacturing resources, which exists in different areas, and access to the service platform. On this basis, it can form a huge intelligent information interaction network to realize intelligent identification, monitoring and management of manufacturing resources. At the same time, among manufacturing enterprises, the effective usage of IoT can aggregate all kinds of resources which are inside and outside the enterprise. Also, it can form an omni-directional, integrated, high covering manufacturing network. Then, it can integrate the manufacturing resources and realize resources allocation in an intelligently and efficiently way. It can eventually achieve the integration of industrialization, information, and intelligent of enterprises, onto the road of green sustainable development.

System architecture consists of resource layer, perception layer, network layer, service layer and application layer, as shown in Fig. 2.

1) Resource Layer: It provides all kinds of manufacturing resources involved in the entire life cycle of manufacturing, and basic resources to the operation of manufacturing service platform. Manufacturing resources mainly include hardware manufacturing resources, computational resources, intellectual resources and other resources. The detailed classifications are shown in Table I.

2) Perception Layer: It achieves intelligent perception and identification of all kinds of manufacturing resources through different sensing devices and adapters in product life cycle, thereby providing strong support for manufacturing service platform to intelligently identify and manage manufacturing resources. Sensing devices include two-dimensional barcode, RFID readers, sensors, video capture and GPS, and so on. The adapter includes software interface adapter, sensor adapters, model adapters, knowledge adapters, network adapters, storage adapters, technical resource adapters, and other kinds of adapters.

3) Network Layer: It provides all needed carrier network for access various resources in products whole life cycle, including 2G networks, 3G networks, 4G networks, satellite networks, cable networks, corporate internal wireless networks, and so on. Construction of the network layer is conducive for numerous,

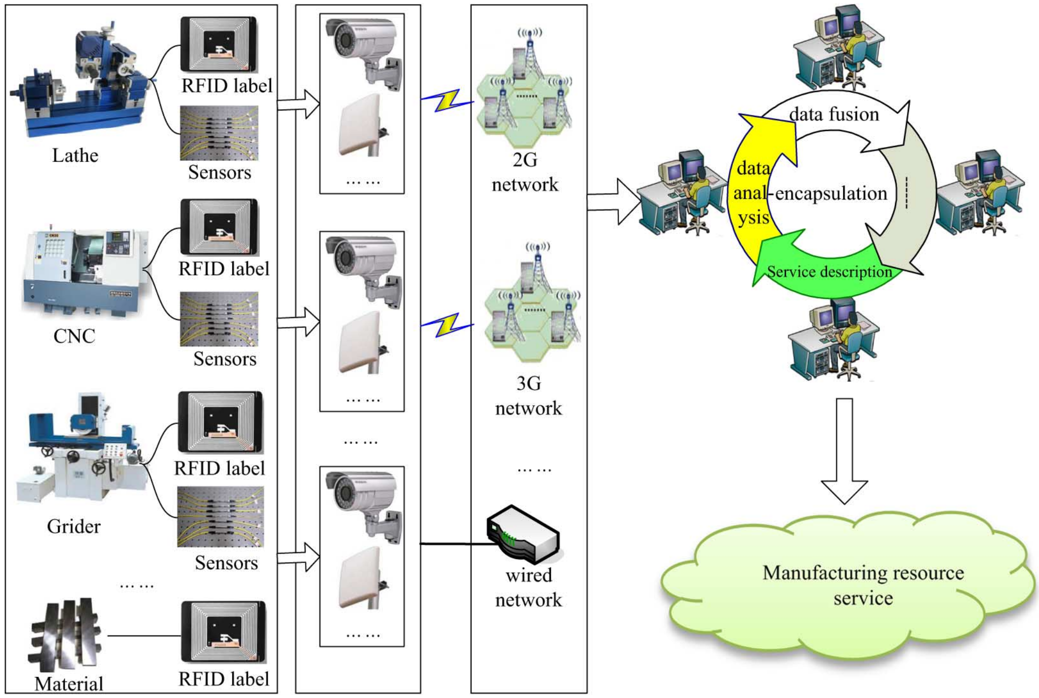


Fig. 3. Perception and access framework of hard manufacturing resources.

security, and high-speed transmission of manufacturing resources, which provides network support for management service layer.

4) Service Layer: It primarily provides two categories of service, the CMfg service and the CMfg platform operational service. The former are the results of service encapsulation of manufacturing resources and capacities, which can be invoked by end users. The latter are the main services provided by the CMfg platform to realize the various operators to CMfg services, which includes knowledge management, transaction management, information assessment, billing management, resource calendar management, network management, virtual machine management, directory management, registration services, and so on.

5) Application Layer: It refers to the on-demand use of various CMfg services in the entire life cycle of manufacturing, including design, manufacturing, experimentation, simulation, management, maintain, recycling, and so on.

V. Intelligent Perception and Access of Manufacturing Resources Based on IoT

A. Perception and Access of Hard Manufacturing Resources

The perception and access process of hard manufacturing resources mainly includes the intelligent perception of hard manufacturing resources, the access of hard manufacturing resources, and the encapsulation of hard manufacturing resources as shown in Fig. 3.

1) Perception of Hard Manufacturing Resources: Equipment resources are mainly perceive the static property information (e.g., equipment suppliers, equipment name, processing capacity information) and the dynamic information (e.g., equipment running state, equipment temperature, etc.). The material information is also divided into static and dynamic information on the same principle. Due to the difference in resource types and the characteristics of sensor data, they are preceived in different ways.

Dynamic information for equipment resources is mainly to perceive real-time status data by installing fiber optic sensors on the key components. While static information is read by the tag that RFID reader device is attached. Material static and dynamic information can be read through the label stores and can be real-time perception through different positions of RFID reader in the enterprise.

2) Access of Hard Manufacturing Resources: Due to the harsh environment of manufacturing process and the real-time change in objects' position, the access methods of the network are different. For a fixed mechanical equipment, the fiber optic sensors are accessed in industrial bus LAN, while it is used for the RFID reader to transfer data to a remote data center by combining wireless network with wired network.

3) Encapsulation of Hard manufacturing Resources: Hard Manufacturing resource encapsulation process is completed by the resource class description templates and implementation class templates jointly. Description class template describes resource-related attribute information, and its aim is to describe the perception data in accordance with a template which will retain required data and filter out irrelevant data. Resource implementation class template is to describe the information in accordance with uniform rules encapsulation and save it.

B. Perception and Access of Computational Resources

The perception and access process of computational resources primarily includes three parts: virtualization of computational

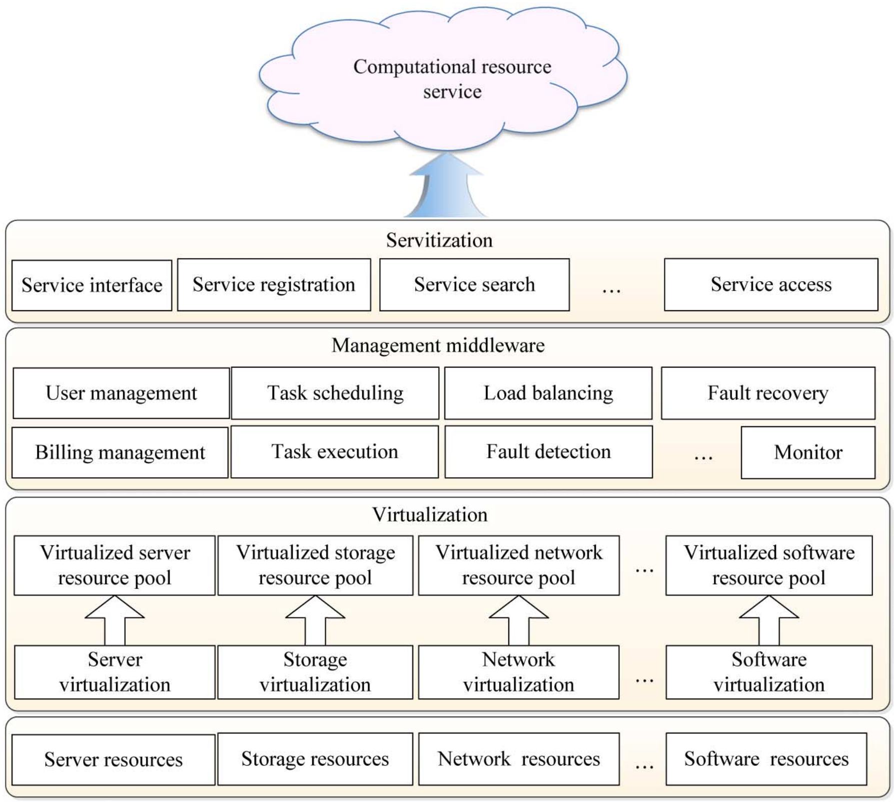


Fig. 4. Perception and access framework of computational resources.

resource, management middleware, and servitization of computational resource, as shown in Fig. 4.

1) Virtualization of Computational Resources: The virtualization of computational resource is consisted of: 1) server virtualization, 2) software virtualization, 3) network virtualization, and 4) storage virtualization.

Server virtualization is the process of abstracting physical resource into logical resource. It can virtualize several servers or even hundreds of computers by installing virtualization software (e.g., VMware). Storage virtualization can also virtualize several storage devices from distinctive areas into one integrated device. Software virtualization holds single application document, registry key, and other relevant configuration in a new figure structure to install and uninstall application, and other functions conveniently.

2) Management Middleware: It located between virtual resource and computational resource services, and it primarily includes user management, task scheduling, task execution, load balancing, fault detection, fault recovery, monitor, and so on. For example, user management can provide the functions such as user identity management, user authority management, user request/registration management, and so forth.

3) Servitization of Computational Resources: It aim to achieve the transformation from virtual resource to computational resource service. It includes service interface, service registration, service search, service access, and so on. For example, the aim of service interface is to convert different types of data to unified information data, and provide support for web services in an interactive environment. A user can register service by using service registration function, and the service search is primarily responsible for match and search the required services for different users and requirements.

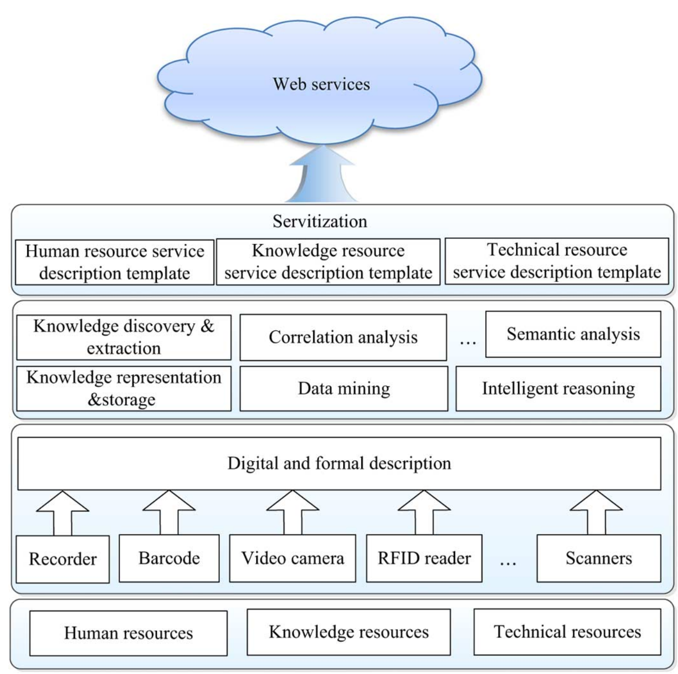
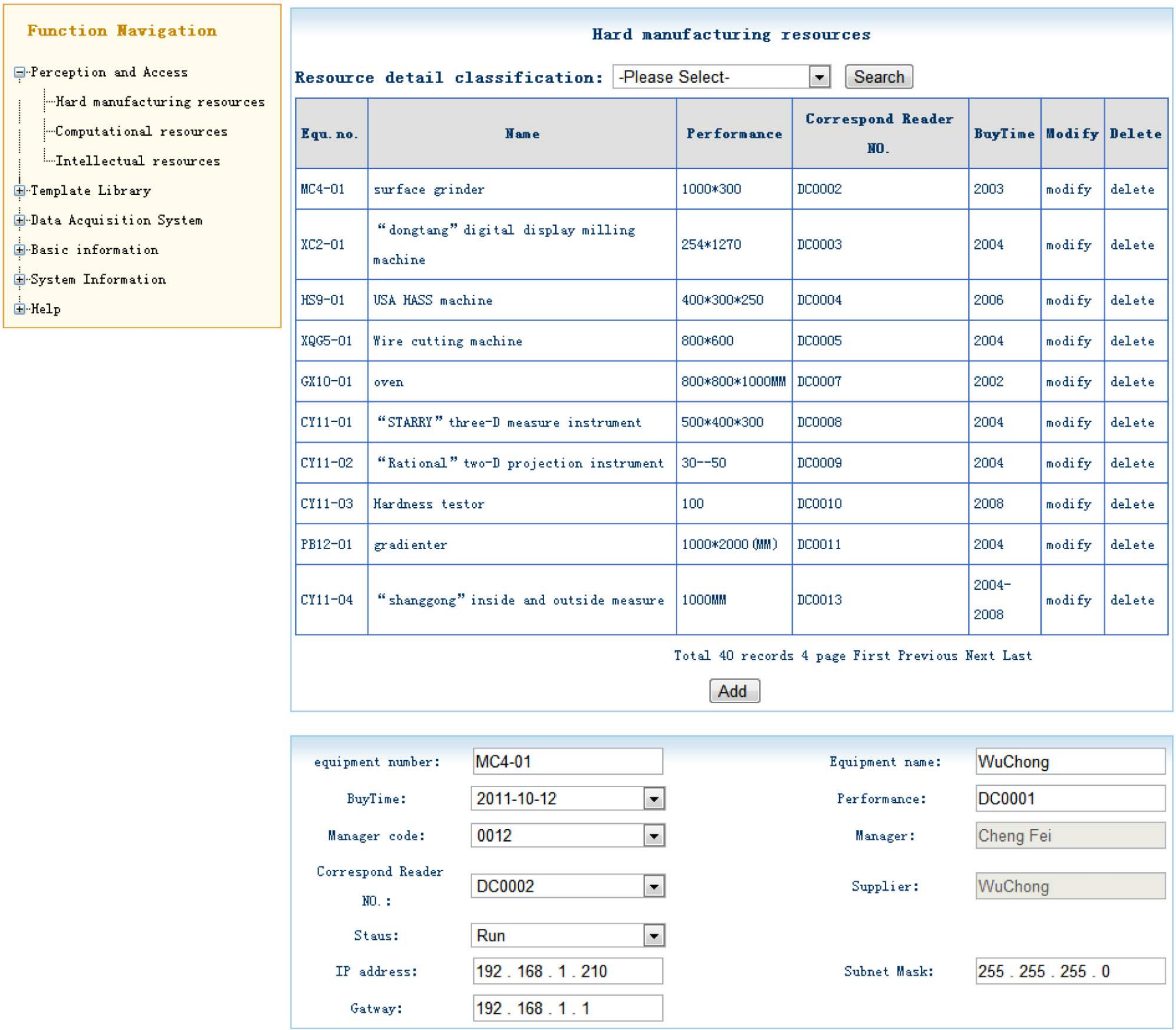


Fig. 5. Perception and access framework of intellectual resources.



Equ. no.	Name	Performance	Correspond Reader NO.	BuyTime	Modify	Delete
MC4-01	surface grinder	1000*300	DC0002	2003	modify	delete
XC2-01	"dongtang" digital display milling machine	254*1270	DC0003	2004	modify	delete
HS9-01	USA HASS machine	400*300*250	DC0004	2006	modify	delete
XQG5-01	Wire cutting machine	800*600	DC0005	2004	modify	delete
GX10-01	oven	800*800*1000MM	DC0007	2002	modify	delete
CY11-01	"STARRY" three-D measure instrument	500*400*300	DC0008	2004	modify	delete
CY11-02	"Rational" two-D projection instrument	30--50	DC0009	2004	modify	delete
CY11-03	Hardness testor	100	DC0010	2008	modify	delete
PB12-01	gradienter	1000*2000 (MM)	DC0011	2004	modify	delete
CY11-04	"shanggong" inside and outside measure	1000MM	DC0013	2004-2008	modify	delete

Fig. 6. Interface of the collected data of the connected manufacturing resource.

C. Perception and Access of Intellectual Resources

The perception and access process of intellectual resource primarily consist of three parts as shown in Fig. 5.

1) Digitization of Intellectual Resources: It includes human resource digitization, knowledge resource digitization, and technical resource digitization. Its process is the perception, and digital and formal description of intellectual resources. For example, the knowledge of human resource, which includes experience and skill, can be obtained by the recorder or other methods. At the same time, one can gain an e-book by scanning the paper book. On this basis, one can get the detained property information with digital and formal description mechanism.

2) Management Middleware: It primarily includes knowledge discovery and extraction, knowledge representation and storage, correlation analysis, semantics analysis, data mining, intelligent reasoning, and so on. The first four content belong to the conversion process of knowledge. Correlation analysis and semantics analysis is to extract the potential useful data, information, and knowledge from intellectual resources.

3) Service Encapsulation of Intellectual Resources: In order to make full sharing and on-demand use of intellectual resources, the obtained useful data, information, and knowledge are encapsulated into services by employing different service description template, such as human resource service description template, knowledge resource service description template, and technical resource service description template.

D. Prototype System of the Proposed Method

In order to verify the proposed technology of intelligent perception and access of CMfg resources, manufacturing resource perception and access systems have been developed. An example about perception and access of manufacturing equipment resources is proposed in this paper to verify the proposed technology. Specific steps are as follows.

1) Manufacturing resource perception and access system mainly have two kinds of users, including enterprise users and operator.

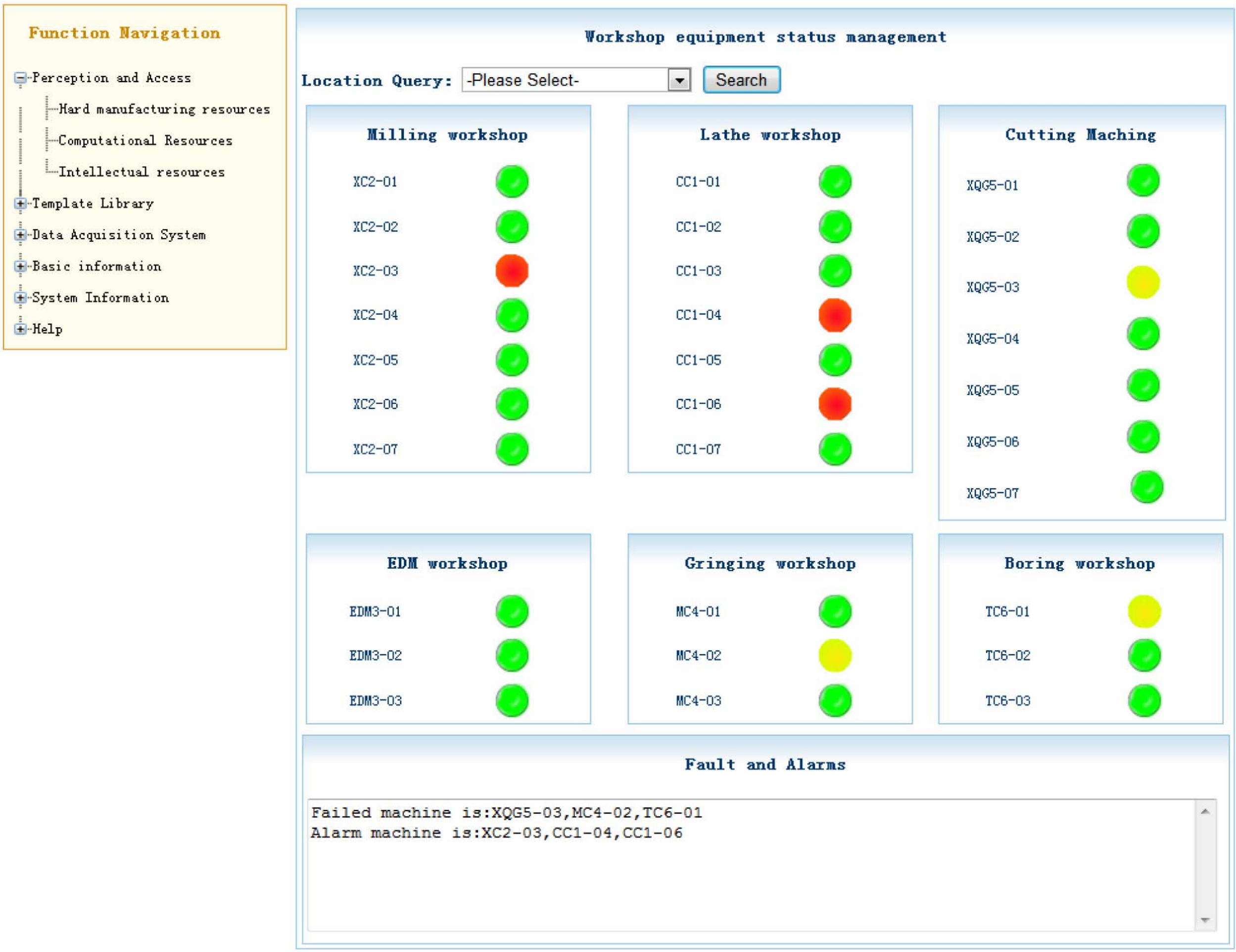


Fig. 7. Real-time status information of the connected manufacturing equipment (red: alarm; yellow: fault; green: normal).

2) When enterprise users login platform, the configuration data of various sensors, the attribute information of manufacturing equipment, and their deployment location information are entered into systems. The detail information mainly includes equipment number, manager code, principle number, the corresponding RFID number, purchase time, performance parameters, and so on. This information will also be written in tags, as shown in Fig. 6.
3) After completing the previous step, enterprise users can look over various basic data. (e.g., shared data and private data). Meantime, one can modify or delete this data too.
4) Bind the accessed fiber-optic sensor to the specific machine tool, fill in the relevant fiber-optic sensor configuration information, and associate them with the related implementation template.
5) When operator login in this platform, they can manage enterprise users and collect their usage fees, and other functions.
6) After obtaining usage permissions, enterprise users login in the system. The location and real-time status information of existing manufacturing equipment can be viewed on users' interface, as shown in Fig. 7.

VI. Conclusion and Future Works

How to realize the intelligent perception and access of manufacturing resources and capabilities is one of the bottlenecks for the implementing of CMfg. Without addressing this problem, the upper operators to manufacturing resource and services would lose the basic information and data supports. Therefore, the efforts have been concentrated on this issue and a new possible idea and potential method for addressing the problem based on IoT and advanced information technologies has been discussed and attempted. The main innovative contributions and the specific works of this paper are as follows.

1) The current advances about CMfg, as well as the three key technologies faced by the implementation of CMfg, have been briefly reviewed. The significant role of intelligent perception, connection and access of manufacturing resources, and capabilities in CMfg has been discussed.
2) The classifications of manufacturing resources and manufacturing services, as well as their relationships, are presented.
3) A potential method for realizing the intelligent perception and access of manufacturing resources and capabilities based on IoT technologies is attempted. A five-layered

framework of manufacturing resource intelligent perception and access system based on IoT is designed and presented, including resource layer, perception layer, network layer, service layer, and application layer.

4) Based on the classification of manufacturing resources and services, the detailed method and framework for realizing the intelligent perception and access of hard manufacturing resources, computational resources, and intellectual resources have been discussed.
5) A prototype application system is developed to illustrate the proposed method.

However, current research to CMfg primarily still stays on the level of theory and framework. Therefore, the above research to resource perception and access in CMfg in this paper is just a preliminary attempt. Before it can be wildly used in practice, there are still many works that have to be done in future. For example, the following works are required and recommended to be further studied in future, including the design, production, and deployment of specific perception devices, equipment, and sensors (e.g., optical fiber sensors for online and real-time monitoring high speed rotating equipment with high working temperature); the standard, protocol, safety and security, reliability, and management technologies of applying IoT in manufacturing and CMfg system; and effective and reliable technologies and devices for data mining and processing to the collected data by using IoT; and so on.

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Fei Tao (M'13), photograph and biography not available at the time of publication.

Ying Zuo, photograph and biography not available at the time of publication.

Li Da Xu (M'86–SM'11), photograph and biography not available at the time of publication.

Lin Zhang (S'05–M'06–SM'13), photograph and biography not available at the time of publication.