Internet of Things for Enterprise Systems of Modern Manufacturing

Zhuming Bi, *Senior Member*, *IEEE*, Li Da Xu, *Senior Member*, *IEEE*, and Chengen Wang, *Senior Member*, *IEEE*

***Abstract*—Design and operation of a manufacturing enterprise involve numerous types of decision-making at various levels and domains. A complex system has a large number of design variables and decision-making requires real-time data collected from machines, processes, and business environments. Enterprise systems (ESs) are used to support data acquisition, communication, and all decision-making activities. Therefore, information technology (IT) infrastructure for data acquisition and sharing affects the performance of an ES greatly. Our objective is to investigate the impact of emerging Internet of Things (IoT) on ESs in modern manufacturing. To achieve this objective, the evolution of manufacturing system paradigms is discussed to identify the requirements of decision support systems in dynamic and distributed environments; recent advances in IT are overviewed and associated with next-generation manufacturing paradigms; and the relation of IT infrastructure and ESs is explored to identify the technological gaps in adopting IoT as an IT infrastructure of ESs. The future research directions in this area are discussed.**

***Index Terms*—Enterprise modeling, enterprise systems (ESs), Internet of Things (IoT), literature review, manufacturing enterprise, system paradigms.**

I. INTRODUCTION

MANUFACTURING is woven into economy and society. For example, manufacturing took 12% of gross domestic product (GDP) and 11% of workforce in the Unites States in 2011 [27]. Moreover, the significance of manufacturing is far beyond the scope these numbers represent. For example, the manufacturing sector in the U.S. used to take 19% of GDP and 30% of workforce in the 1950's [53]; however, this percentage has been shrinking continually for several decades. More enterprises have relocated their facilities to developing countries and it has shown that the manufacturing industry in the U.S. is still in recession [24], [75]. Therefore, identifying new drivers to boost manufacturing is crucial to regain the leading position in manufacturing.

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Z. Bi is with the Department of Engineering, Indiana University–Purdue University Fort Wayne, Fort Wayne, IN 46805 USA (e-mail: biz@ipfw.edu).

L. D. Xu is with the Institute of Computing Technology, Chinese Academy of Sciences, Beijing 100190, China; Shanghai Jiao Tong University, Shanghai 200240, China; University of Science and Technology of China, Hefei 230026, China; and also with Old Dominion University, Norfolk, VA 23529 USA.

C. Wang is with the State Key Laboratory of Synthetical Automation for Process Industries, Northeastern University, Shenyang 110819, China (e-mail: wangc@mail.neu. edu.cn).

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The advance of manufacturing technologies relates closely to information technologies (ITs). Since design and operation of a manufacturing system needs numerous types of decision-making at all of its levels and domains of business activities, prompt and effective decisions not only depend on reasoning techniques, but also on the quality and quantity of data [26]. Every major shifting of manufacturing paradigm has been supported by the advancement of IT. For example, the widely adoption of computer numerical control (CNC) and industrial robots made flexible manufacturing systems (FMSs) feasible; the technologies for computer-aided design (CAD), computer-aided manufacturing (CAM), and computer-aided processing planning (CAPP) made computer integrated manufacturing (CIM) practical. In developing their ESs, more and more enterprises rely on the professional providers of IT software service to replace or advance their conventional systems [56]. Therefore, it makes sense to examine the evolution of the IT infrastructure and evaluate its impact on the evolution of manufacturing paradigms, when a new IT becomes influential.

We are motivated to investigate the impact of IoT on system paradigms, when IoT can be applied in modern manufacturing enterprises. To achieve this objective, both the evolutions of manufacturing paradigms and IT are discussed. Their relations are explored to identify the priorities of the subjects of research and development. In Section II, the evolution of manufacturing system paradigms is introduced and the focuses are enabling technologies for ESs. In Section III, the IT development is discussed; its impact on manufacturing technologies has been discussed. In Section IV, the progress of emerging IoT is introduced, and some potential issues related to its application of ESs in modern manufacturing are explored. In Section V, the reported work is summarized and future research activities of adopting IoT in ESs of modern manufacturing are discussed.

II. EVOLUTION OF ESs

A manufacturing system is to produce value-added goods via various manufacturing resources such as machines, tools, and labors. Design and operation of a manufacturing system involves numerous types of decision-making at all levels and domains of manufacturing activities. System components and their relations can be represented by enterprise architecture [7]–[9], which will be discussed further in Section II-B. In any system or sub-system, a decision-making process can be depicted as a series of design activities:

1) defining the scope and boundary of a design problem and its objective;
2) establishing relational models among inputs, and outputs, and system parameters;

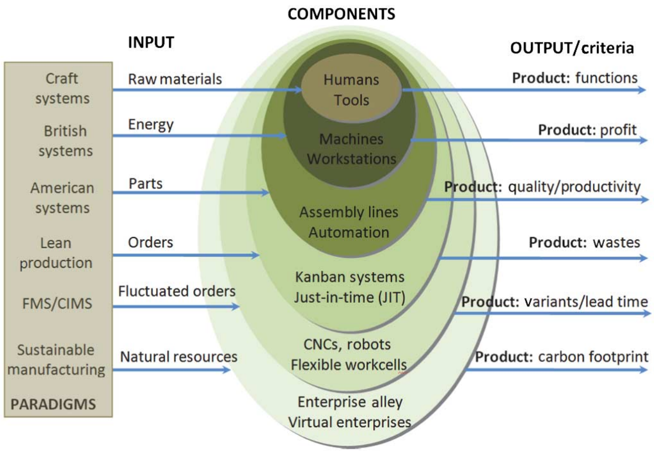

Fig. 1. Evolution of inputs, outputs, and system components.

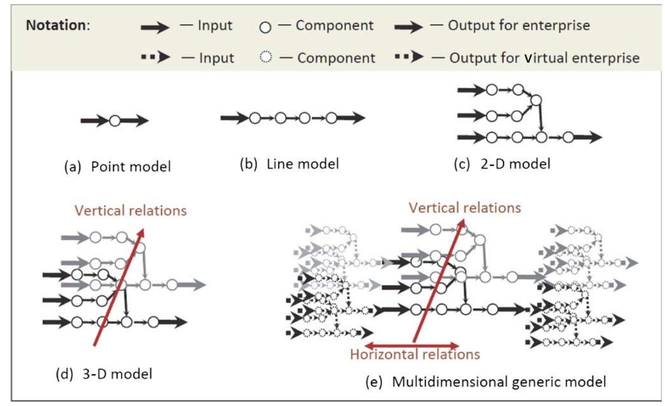

Fig. 2. Types of system models.

3) acquiring and managing data on current system states;
4) making decisions according to given design criteria.

An ES is to acquire and maintain data, and serve as a decision-making system within an enterprise. Therefore, the characteristics of an ES can be examined from the perspective of decision-making processes.

A. Description of Manufacturing Enterprise

The complexity of system operations relates directly to the number and nature of inputs, outputs, and other system components. Many researchers have discussed the evolution of manufacturing technologies. The differences of scopes and boundaries of a manufacturing enterprise are focused here. In particular, inputs, outputs, and system parameters are examined. Note that *system parameters* are used to represent system components and relations; they can be classified into *structural parameters* as the representations of system properties and *design variables* as the factors changing with respect to time. Inputs and outputs are typically the variables representing the interactions of the system and its environment.

Fig. 1 has illustrated the evolution of manufacturing systems, which is divided into the phases of *craft systems*, *British systems*, *American systems*, *lean production*, *FMSs/CIM* [23], and *sustainable manufacturing* [10]. With the evolution of a manufacturing system, inputs, outputs, as well as system parameters can be changed with respect to time significantly. One can find that design variables have being increased exponentially with the evolution of manufacturing systems. A detailed discussion on the similar subject has been covered by Galbraith [36]. Moreover, the adoption of the Internet has significantly influenced the enterprises on how the profits are shared by participants over their supply chains [35], [52], [55], [76]. The information systems for the next-generation manufacturing systems must accommodate the changes of the IT infrastructure as well as the changes and uncertainties in the system environments.

B. Reference System Models

Reference system models describe the constitutional components and their interactions within a system according to desirable system performances. An enterprise model represents basic system elements, relationships, and the refinements up to the necessary level of details. Conceptual models and architectures of manufacturing enterprises have been extensively studied. A few of widely used enterprise models were discussed in the literature [15], [34], [63], [67], [74], [85], [91], and [94]. However, conventional enterprise models are static, which lack of capability to accommodate changes. Some advanced concepts, such as *holonic manufacturing*, *agent-based intelligent manufacturing*, *reconfigurable manufacturing*, and *agile manufacturing* [7], [8], [10], have been proposed to be integrated with enterprise models to increase system adaptability and flexibility. Tao *et al.* [82] discussed a service-oriented manufacturing paradigm for *cloud manufacturing*, where both of computational and manufacturing resources are managed simultaneously. Xu [92] discussed the architecture of information systems for supply chain management. Recent progresses of enterprise modeling, ESs, and the integration of distributed enterprise applications have been discussed comprehensively [10], [45], [66], [93].

Fig. 2 has classified system models from the perspective of system complexity. A craft system completes all activities at one machine station and it can be viewed as a *point model*. Later on, a transfer line organizes all manufacturing activities sequentially; the corresponding system model is a *line model*. Manufacturing systems are then expanded to multiple transfer lines and multiple factories; therefore, the relational models can be described as *two-and three-dimensional models*, respectively. With the appearances of enterprise alliances and virtual enterprises, system components will cover related resources from enterprise partners and virtual enterprises, which are beyond the boundary of one manufacturing enterprise. It is another perspective to show the increased complexity of manufacturing enterprises.

C. Data Acquisition and Management

Design variables represent for the states and the changes of inputs and outputs with respect to time. Acquiring the values or states of the variables is essential to support closed-loop decision-making. Data acquisition is to collect data by sensors or other measurement equipment. Although data acquisition covers manual monitoring and recording methods such as inspecting a product visually or measuring an object, data acquisition generally refers to the use of electronic sensors and data collection equipment [51]. Early manufacturing systems were open

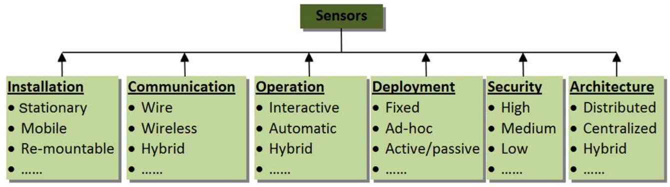

Fig. 3. Classification of data acquisition system [20].

loop; with few sensors, humans played a central role in observing the system's behavior and making decisions accordingly. Technologies for data acquisition and processing have been rapidly evolved with the automated solutions. In Sections II-C1 and II-C2, *data acquisition* at the device level and the *data communication* are discussed as follows, respectively.

1) Data Acquisition: Sensors or device for data acquisitions are crucial to the success of new products [71]. Instrumentation usually consists of some basic elements to collect, process, and share data among objects. Hardware systems for data acquisition instrumentation have been classified in Fig. 3. Instruments are much diversified in terms of the functions, communication modes, and other factors. With an increase in system components in a system, how to collect, fuse, process, and use data effectively, becomes very challenging.

2) Communication for Data Sharing: Data communication is to exchange data among different devices via some transmission medium such as wire cables and wireless networks. In a manufacturing enterprise, data are communicated and exchanged among decision-making units locally or remotely. The performance of data communication can be evaluated by *delivery*, *accuracy*, *timeliness*, and *jitter*. Communication and networking are changing the way an enterprise operates its business. Operating decisions have to be made quickly, and the decision support system units require an instant access to sufficient and accurate real-time data. The availability of data relies on reliable communication and network [33].

Gungor and Lambert [41] gave a comprehensive survey on the networks for data communication, and four phases described by them are as follows.

1) The first phase was the nonstandardized communication before 1985. Network architecture was hierarchical. It was solo master or isolated substations and the communication media were dial-up, RS232, and trunked radio. The communication rate was less than 1200 bps.
2) The second phase was the standardized communication during 1985–1995. Communication media were wired lines and packet radio. The communication rate was in a range of 9600–19 200 bps.
3) The third phase was the communication via the networks that happened from 1995 to 2000; the Ethernet and spread spectrum radio were adopted widely. The transmit rate reached at megabit level.
4) The last phase started from 2000. The media such as Internet Protocol (IP) radios and wireless Ethernet are used. The transmission rate is over gigabit.

Communications can also be classified in terms of *channel types*, *channel interfaces*, *data rates*, and *applications*. For examples, the types of channel interfaces include dc *signaling* for telegraph, *narrowband modems* for sub-voice grade, 2/4 *wire modems* for leased voice grade lines, 2-*wire modems or acoustic couplers* for switched telephone network, *digital station terminal* for digital service, *Wideband moderns* for wideband analog, *Line drivers* and limited distance modems for private cable, and *fiber optic* connector and fiber optics [40].

D. Critical Requirements to Adapt New Environments

A complete ES generally includes system components for *data acquisition*, *communication*, *data management*, and *decision-making*. ESs should be designed to meet the requirements of modern manufacturing enterprises for these functionalities. From the discussions in this section, we can summarize the new requirements as follows, which form some critical challenges to ESs.

1) *Complexity*: Ever-increasing complexity is contributed by two key factors: 1) Modern products become versatile which need more parts and components to fulfill required functions. Manufacturing resources have to be integrated vertically to make these products. 2) Making complex products involves numerous manufacturing activities. Sometimes, it even becomes impractical to perform all activities within an enterprise. In this case, enterprises have to be allied the partner enterprises along the supply chain horizontally. The hierarchy enterprise model with vertical and horizontal integration of business departments in one enterprise is ineffective to deal with such a level of complexity.
2) *Dynamics and uncertainties*: Manufacturing environments are dynamic. Traditional ESs divide the time domain into sub-periods so that system parameters involved in one decision-making task can be treated statically within an individual period; the complexity of decision-making is manageable. When an enterprise model becomes flat, complex decisions have to be made within a shorter period. It becomes extremely important to know the changes and uncertainties in real-time; and share real-time data over entire ES. Zeng and Skibniewski [96] conducted the risk assessment in enterprise resource planning systems and the fault tree approach was used to analyze uncertainties and risks. Corrales *et al.* [22] studied the autonomous navigation of an indoor robotic system with a focus of the information system in the unknown environment. Chamdrashekhar and Bhasker [18] discussed the impact of information uncertainty on automated negotiation and developed new negotiation model to improve the efficiency, simplicity, and stability.
3) *Virtual entities*: Manufacturing resources have to be integrated to make a balance between the manufacturing capabilities and system flexibilities, i.e., physical and virtual resources can be considered simultaneously to provide sufficient capabilities to make complex products. The information systems of a host enterprise and its collaborating virtual enterprises must be integrated to optimize the collaboration globally. However, the ownership of data from an individual participator might bring barriers to share the data seamlessly for effective decision-making.

4) *First-time correct*: The fierce competition forces enterprises to minimize nonvalue added activities such as buffering and repairing. To keep competitiveness, an enterprise must organize its manufacturing activities to avoid carrying excessive inventory and make product correct at the first time. On the one hand, the production line should be monitored to avoid the breakdown of machines. If an error happens on one workstation, the whole production line will be affected. On the other hand, the product quality has to be strictly controlled; defected parts, components or products increase the cost for end products. Both of the efforts need reliable and real-time data about products, processes, and resources. The states of a manufacturing system should be monitored thoroughly and real-time data about everything should be available to make right decisions at different domains and levels.

E. Limitations of Existing Work

Existing manufacturing paradigms and control methodologies are continually facing new challenges to meet these requirements in a competitive environment. The following limitations are observed in meeting these challenges.

Unbalance of software and hardware flexibility: The flexibility of a manufacturing system is required to deal with changes and uncertainties [11]–[14]. System flexibility relies on both of hardware and software systems and it can be maximized if the flexibility of hardware and software systems is balanced. While the flexibility of existing hardware systems seems to reach its limits as far as the cost is concerned, the flexibility of software systems is mostly unsatisfactory. Good examples are industrial robots and FMSs. Hardware systems such as industrial robots are able to take task variations; however, they have to be reprogrammed for new tasks. For many advanced applications, it is still a big challenge for the software system to acquire and process sufficient data, and generate the program automatically and promptly to changeable tasks.

Information islands: The problem of the isolation of information sub-systems has been observed by many researchers [30], [92]. The isolation not only happens to the top level of decision-making, but also happens at device or sub-system levels where raw data of machine status are collected. Within a large-scale and complex system, information islands bring the delay in information communication and sharing; for the cases where the historical data are required by different components for decision-making; the cost for storage and computing is increased and additional care has to be taken to maintain the consistence of data.

Redundant resources: Computing resources are needed by any decision-making units. Data usually need to be stored and complex decisions are made locally. On the one hand, a number of high-performance computers are required to support distributed decision-making; this increases the cost of an ES; the computing capability is not fully utilized if it can only be accessed locally. On the other hand, the distributed resources bring a problem of synchronizing data, the requirements of multiple decision-making units make it impractical to be equipped with the highest computing power of an ES.

Encapsulation of system components: Components in an ES are generally encapsulated and fully protected from its manufacturing environment. This brings the obstacles for customers to know manufacturing processes or learn more requirements about their products. It is particularly true when the system sustainability becomes a critical factor to today's enterprises. The customers in supply chains play a mixed role with suppliers, users, and even designers. Data collection, exchanges, and sharing over the whole product life cycle become more and more important.

III. Evolution of IT Infrastructure

Primary functions of an ES are: 1) to acquire static and dynamic data from objects; 2) to analyze data based on computer models; and 3) to plan and control a system and optimize system performances using the processed data. The implementation of a manufacturing system paradigm relies heavily on available IT. In this section, the IT infrastructure related to manufacturing is discussed. IoT has been identified as a critical technology with its great impact on the national economy [64]. Here, an overview about the history, core components, and advantages of IoT is given.

A. Overview of IoT

The Internet has changed the business and personal lives in past years and continued doing so. IoT becomes a foundation for connecting things, sensors, actuators, and other smart technologies [83]. IoT is an extension of the Internet [32]. IoT gives an immediate access to information about physical objects and leads to innovative services with high efficiency and productivity [6]. Arguable pioneers of coining the concept of IoT are Bill Gates, Kevin Ashton, and Neil Gershenseld at Auto-ID Center of Massachusetts Institute of Technology (MIT) [4], [72]. The first IoT conference was held in Europe in 2006. Participators included over 50 member companies such as Intel, SAP, Sun, and Google. IoT has not been applied as people expected; however, it is predicted as a combination of a number of advanced IT technologies, which will drastically change our societies in 5–15 years [17].

For the hardware and system development, several significant milestones related to IoT are the Auto-ID Center at MIT in 1999, the Internet Refrigerator at LG in 2000, the Ambient Orb by David Rose in 2002, "smart earth" project by IBM in 2008, and "experience China" project in 2009. Bandyopadhyay and Sen [6] overviewed key technological drivers, potential applications, and challenges in IoT. The identified central issues are interoperability, interconnected objects, and enabling the adaptation and autonomous behaviors with trust, security, and privacy of users. Zorzi *et al.* [98] discussed how existing "intranet" of things can be evolved into an integrated and heterogeneous system.

B. Core Components and Enabling Technologies

The characteristics of IoT include: 1) the pervasive sensing of objects; 2) the hardware and software integration; and 3) a large number of nodes. Bui [14] discussed enabling technologies for IoT including architecture frameworks, communications, standardizations, modeling techniques, communication protocols, identification, objects platforms, and security and privacy. Atzori *et al.* [5] surveyed key enabling technologies and discussed the progress made on communication, identification, tracking, wired and wireless sensors, and distributed intelligence for smart objects. Since two of the most important technologies to IoT are radio-frequency indemnifications (RFIDs) and wireless sensor networks (WSNs) [88], besides ubiquitous computing and cloud computing, the studies on RFIDs and WSNs are discussed as follows.

1) Ubiquitous Computing: The Internet can be described as a ubiquitous infrastructure. IoT is also known as ubiquitous computing, ambient intelligence, and distributed electronics. In an IoT, a virtual computer model can be seamlessly integrated with physical networks of objects [83]. For example, Fang *et al.* proposed an integrated approach based on the sensor network for water resource management [31]. IoT will change the ways of managing and operating production, distribution, transportation, service and maintenance, recycling of their products.

Ubiquitous computing is enabled by smart devices. Smart devices are capable of: 1) applying data mining and analysis, modeling and simulation, fusion and computation, and scientific analysis for decision-making; 2) integrating personal device, organization, and other information systems for interacting, data sharing, and real-time monitoring; and 3) using anytime, anything, anywhere communication to sense, measure, capture, and transfer data in planning and scheduling. For individual smart devices, their performances have been improved greatly. They become versatile, powerful, and intelligent to deal with changes and complexity. For the networked system, simple devices without superior computation capability can be integrated; abundant information can be acquired for real-time decision-making. In developing an IoT, objects must be capable of interacting with each other, reacting autonomously to the changes of residential environment, and responding people appropriately [84].

2) RFIDs: RFID has been widely applied in modern manufacturing, in particular, in supply chain management [16], [54]. RFID is one of the cornerstones of IoT [28]. RFID was initially developed to track and identify objects in retails and logistics. In near future, single numbering scheme including Internet Protocol version 6 (IPv6) will make it possible to identify every single object. However, to achieve ambient intelligence, major technological innovations are in demand. These include governance, standardization, and interoperability [46], [69], [86], [89], [95], and efficient and secure communication protocols. Furthermore, other major research challenges are to enable device adaptation, autonomous behavior, intelligence, robustness, and reliability.

3) Wireless Sensor Networks: IoT is a network of all physical objects with identifiable IDs, which are based on the Internet or other conventional communications. Early work on IoT was the application of Auto-ID for the supply chain management. IoT in near future will provide a wider application by enabling individuals to acquire and take advantage of abundant data from objects [82]. For example, Li *et al.* discussed how networked body sensors could assist in obtaining biomedical signals continuously [58]. The integration of WSNs was discussed to provide cloud services to enterprises [59]. WSNs are the most important infrastructure for the implementation of IoT. Various hardware and software systems are available to WSNs:

1) IPv6 makes it possible to connect unlimited number of devices.

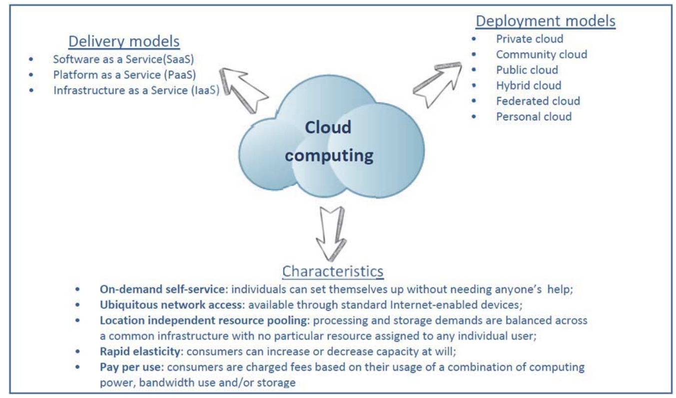

Fig. 4. Characteristics of cloud computing.

2) WiFi and Wimax provide high-speed and low cost communication.
3) Zigbee, bluetooth, and RFID provide the communication in low-speed and local communication.
4) A mobile platform offers communications for anytime, anywhere, and anything.

The importance of WSNs to industrial control systems have been discussed by Araujo *et al.* [3]. In the research field of WSNs, most of ongoing work focuses on energy efficient routing, aggregation, and data management algorithms; other challenges include the large-scale deployment and semantic integration of massive data [1], and security [38].

4) Cloud Computing: Cloud computing is a large-scale, low cost processing unit, which is based on the IP connection for calculation and storage. The characteristics of cloud computing have been discussed in the literature [70], [73], [78], [79] and summarized in Fig. 4. The characteristics such as on-demand self-service are essential to support a computing cloud for an enterprise in terms of cost reduction, system flexibility, profit, and competiveness. Wang *et al.* provided cloud service architecture for enterprises [87]. Besides, the benefits of cloud computing to manufacturing system have been explored by some researchers. Cheng *et al.* [19] investigated an information system to schedule services based on energy saving in a cloud manufacturing system. Tan *et al.* developed a grid-based operation platform to support virtual enterprises [80]. Li *et al.* discussed the modeling issues involved in the integration of a hybrid cloud computing environment [56].

C. Applications

IoT is IT infrastructure, which is applied to measure, identify, position, track, and monitor objects. IoT makes people's lives easier and automates our tasks [29]. IoT connects physical objects as a network so that these objects can be interacted effectively [55]. Domingo [25] provided an overview of IoT in assisting peoples with disabilities. Jara *et al.* [45] proposed an IoT-based solution for personalized health care systems. Many new businesses have been developed via the application of IoT [2]. For examples, Gama *et al.* [37] applied service-oriented middleware to enhance system flexibility and dynamicity. Large scale applications are emerging in many industries, such as IBM, Cisco systems, and GE, from smart grid to real-time transportation management and optimization. Although IoT is at its infant stage, 43% of large Chinese organizations started to investigate private clouds and infrastructures, and this number would be increased to 88% in two years [80].

D. Challenges

Currently, the IoT is all about information visibility, it is not about autonomous decision-making. The combination of automated decision-making and IoT will offer a higher level of system robustness, scalability, and agility. Traditionally, the IT standards in enterprises are different from those for commercial software tools. To adopt an IoT, IT infrastructure should be service oriented so that different functions can be integrated over heterogeneous platforms [77].

Jeffery [47] and Cooper and James [21] discussed the challenges of data management in IoT. Atzori *et al.* [5] argued that it is challenging to enable the adaptation and automation for a high degree of smartness, and assure the security and privacy. A new infrastructure is in demand to meet these challenges. Moreover, the Web is growing not arithmetically but exponentially [68]. To deal with a large amount of data, Li *et al.* [56] proposed a compressed sensing theory to eliminate redundant data in data acquisition and transmission in the applications of WSN and IoT.

Standardization is another important issue for system integration [48], [49], [50]. Jakobs *et al.* [44] discussed how to adapt the standards for IoT to meet customers' requirements. The works on standardization have been classified and analyzed, major standards have been identified, and some typical application scenarios have been developed. Alam *et al.* [2] discussed the security issue of IoT-enabled services and interoperability in different domains; as a result, the layered architecture of IoT has been proposed. Welbourne *et al.* [90] developed a building-scale, community-oriented infrastructure. To make IoT application successful, software engineering must fulfill the requirements of heterogeneity, dynamicity, and evolution. Heer *et al.* [43] used the building automated control as an example to illustrate the challenges in a secure IP-based information system.

IV. IoT for Modern Manufacturing

In this section, the relations of new manufacturing paradigm and IT infrastructure are considered. The requirements of an enterprise model for a successful adaption of IoT are discussed.

A. IoT Infrastructure for Enterprises

The aforementioned discussion has shown that IoT is aligned well with the architecture of a manufacturing enterprise. An enterprise model consists of a set of modular components and their interactions. Correspondingly, each system component in an ES needs an information unit to make decisions on the component's behaviors based on the acquired data. Moreover, data acquisition, communication, and decision-making are essential functions for each module. Fig. 5 illustrates the relations of the components in a manufacturing enterprise and the architecture of IoT. Based on the Axiomatic Theory, the IoT is able to provide vital solutions to planning, scheduling, and controlling of manufacturing systems at all levels.

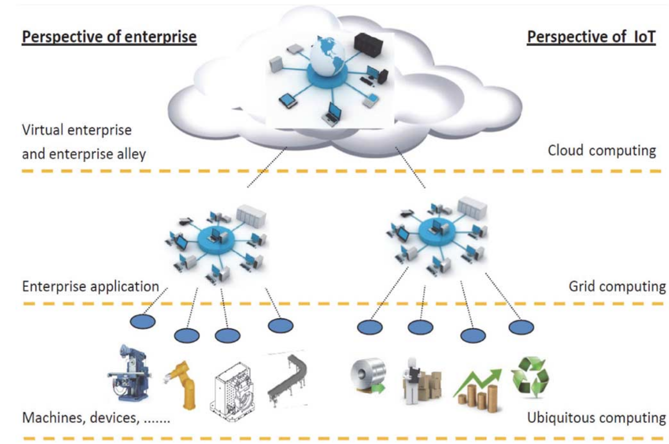

Fig. 5. IoT for modern manufacturing.

B. Features of Next-Generation Enterprises

In this section, the features of next-generation enterprise are discussed to evaluate if an IoT-based ES is capable of meeting these challenging requirements.

1) Decentralized Decision-Making: Domains and levels of manufacturing activities are increasing and becoming diversified. Hierarchical architecture is used to the most efficient enterprise architecture for system integration. However, system complexity can be increased exponentially with the system scale and dynamics. A centralized system may lead to a significant time delay and inflexibility to respond changes promptly. Therefore, distributed and decentralized architecture would be effective means to deal with system complexity and dynamics.

2) Flat and Dynamic Organization: Prompt responses to uncertainties require distributed and decentralized enterprise architecture. In such a way, acquired data can be directly used for decision-making in real time. As far as the interactions among system components are concerned, it forms the challenges to distribute the information to associated components; in particular under a centralized structure. The data are collected and sent to the center database, and then it is sent to an object when the system receives the request from this object. However, a centralized model has its challenges in dealing with massive data and the heterogeneity of environment.

a) Massive data: From the perspective of data management, information systems for next-generation manufacturing enterprises are facing two situations: 1) the cost for decision-making unit is likely increasing with system complexity and the need of fast responsiveness and 2) it causes resources redundant to maintain data locally and the wastes of time and resources for communications when the data are shared by other decision-making units.

b) Heterogeneous environment: Increased and diversified manufacturing resources have increased the heterogeneous nature of a manufacturing environment. The variety exists at the aspects of personalized products, geographical distribution, cultures, suppliers, regulations, optional operations, and standards.

c) Agility and adaptability for real-time changes: Manufacturing enterprises are functioned to meet customers' needs, including functionalities, quantity, quantity, delivery time, and changes. The enterprises must be capable of dealing with changes at reasonable time and making products available as early as possible to catch the market niche. Without such a capability, the profit margin will be reduced significantly.

d) Reconfigurable capabilities: To increase system flexibility, the structures of hardware and software systems are not static anymore. A system at a certain time can be decomposed into sub-systems, and these sub-systems can be reconfigured as manufacturing resources for other tasks. Extra system components are required to support hardware and software system configurations. System reconfigurability or modularization decides the interoperability, which is extremely important in the globalized market. The recent progress on reconfigurable machines was discussed by Bi *et al.* [10].

C. Features of IoT for Manufacturing Applications

1) Integrated Networks of RFIDs and WSNs: One core function of IoT is as the communication infrastructure for data acquisition and sharing. A manufacturing system consists of numerous sensors to acquire real-time data of actuators, machine tools, fixtures, and conveyors; traditional wired communications are confined as point-to-point or peer-to-peer, and it is inflexible to make changes. RFID and WSN provide an effective means to support the distribution and decentralization of manufacturing resources [87].

2) Dynamics: The architecture of IoT is not static, which allows the system components be reconfigured anytime when it is needed. It facilitates the information integration across the boundaries of enterprises. A host enterprise can incorporate with virtual enterprises and establish dynamic relations for a specific project. The organizations can be dismissed when the project is completed and the enterprise can be ready for other projects. The enterprise has its authority in controlling the reorganization of virtual enterprise alley.

3) Cloud Computing: Operation of a modern enterprise involves numerous decision-making activities, which requires intensive information and high capability of computing. Manufacturing enterprises used to require multiple computing resources as servers as databases and decision-making units. This causes the wastes of investment, unbalanced utilization of manufacturing resources, low productivity, and ineffective data exchanges among servers. Cloud computing provides a vital solution to those problems. All data can be stored in private or public cloud servers, and the complicated decision-making can be supported by superior cloud computing.

4) Human and Things: Interactions happen between human and human, human and thing, and thing and thing. Different interactions used to have different mechanisms to support these interactions. With the development of IoT, all of the interactions can be performed under the same umbrella. In this way, participators are able to focus on tasks instead of worrying about interactions, which make the designs and operations of manufacturing systems very productive. In human–machine interaction, how to represent human behaviors in virtual environment is critical, Tao *et al.* [81] discussed the recognition of human behaviors in WSN.

5) Merging IoT in ESs: Changing trends of manufacturing paradigms have been explored by many researchers [8]. In this section, the needs of modern manufacturing and the features of IoT are compared to see how modern manufacturing can benefit greatly from the adoption of IoT infrastructure. It is found that critical needs on the next-generation ESs are consistent to core features the IoT can provide. The manufacturing systems can benefit greatly by adopting IoT infrastructure at all aspects of the information systems including data acquisition, communication, and decision-making at higher levels. The evolution of ES has been discussed by many researchers. For example, Neal [65] provided a roadmap of IT to describe the evolution of information system from manual operation of the databases based on service-orientated architecture. In addition, the impact of IT on manufacturing systems has been discussed as well. Information systems are the key to the success of manufacturing systems; the advancement of information systems is revolutionizing manufacturing systems. By comparing the features of next-generation of ESs in Section II-B and those of IoT in Section IV-C; it is found that the integration of IoT within an ES can be expected to address the challenges of ESs adequately.

1) Ubiquitous computing and grid computing can be applied to network manufacturing resources. Everything can be connected, so that the data can be acquired promptly and readily shared by all decision-making units. This makes it possible to integrate manufacturing resources at a very broad scope, including the resources within an enterprise and virtual resources from potential participators in a supply chain.
2) Customers are empowered by the IT through electronic commerce (e-commerce). Besides the privilege of comparing products from different vendors around the world, IT allows customers to personalize product requirements, place and change orders in real time based on their needs. On the one hand, the satisfaction level of customers can be enhanced greatly from the customers' perspective; on the other hand, many new variables for uncertainties and changes are involved in the management and operations of an enterprise's business.
3) A network-based environment fully supports the collaboration of design, manufacturing, and assembly among different partners. The system is targeted to an optimal balance of flexibility and efficiency. On the one hand, the manufacturing system is modularized; each module is optimized at the module level for its specified function; on the other hand, the selection of modules and assembling topologies offer system flexibility to meet various functions at the system level. Moreover, the topology of system configuration can be optimized with the available global information over the system. The phases of system design, reconfiguration, and deployment are highly corresponded.
4) Information integration connects design database, data acquisition, monitoring, and diagnosing together to assist in making right products without iterations. Traditional information systems are mainly at the macro level planning and scheduling, and such systems will be integrated with real-time control systems at the hardware level. Online data

acquisition systems are not only used to serve for real-time control for machines, but also provide feedbacks about the changes and uncertainties to high-level system planning and controlling. The plans and schedules can be adjusted to accommodate changes and uncertainties promptly. A good example is the changing trend of systems applications products (SAP) software tools; SAP tools are used to focus on the enterprise resource planning before 2005; they have been integrated with manufacturing execution systems. With the emerging of IoT, they would be integrated with online process control eventually [61]. In contrast to hierarchical enterprise architectures, service-orientated architectures become prevalent in industries to improve system flexibility and seamless transition of reconfiguration [38].

V. Summary and Planned Work

Current manufacturing environment has been extensively discussed to identify key requirements of ESs of modern enterprises. It has concluded that the limitations of ESs are: 1) static IT architecture incapable of dealing with all types of changes and uncertainties; 2) unbalanced flexibility of hardware and software systems; 3) rigid and confined boundaries of an enterprise with the barriers for virtue collaboration; and 4) the lack of the considerations on system sustainability. A comprehensive literature review is given on IoT infrastructure, and the opportunities and challenges are explored when manufacturing enterprises adopt IoT infrastructure in their ESs.

It is found that the emerging IoT infrastructure can support information systems of next-generation manufacturing enterprises effectively. More specifically, anytime, anywhere, anything data acquisition systems are more than appropriate to be applied in collecting and sharing data among manufacturing resources. Ubiquitous computing effectively supports mutual interactions among humans and things seamlessly, and cloud computing utilizes superpower computing resources to solve complicated decision-making problems at any level and disciplines. IoT brings numerous great opportunities to advance manufacturing enterprises in achieving better system performances in globalized and distributed environments. However, the application of IoT in ESs are at its infant stage, more researches are in demand in the areas such as modularized and semantic integration, standardization, and the development of enabling technologies for safe, reliable, and effective communication and decision-making.

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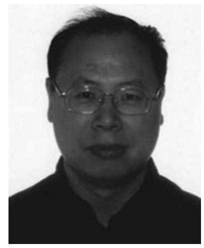
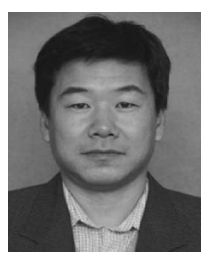


Zhuming Bi (M'11–SM'12) received the Ph.D. degrees from the Harbin Institute of Technology, Harbin, China, and the University of Saskatchewan, Saskatoon, SK, Canada, in 1994 and 2002, respectively.

He is an Assistant Professor of Mechanical Engineering at Indiana University–Purdue University Fort Wayne, Fort Wayne, IN, USA. His current interests include mechatronics, automatic robotic processing, reconfigurable manufacturing, and assembling systems.

Li Da Xu (M'86–SM'11) received the M.S. degree in information science and engineering from the University of Science and Technology of China, Hefei, China, in 1981, and the Ph.D. degree in systems science and engineering from Portland State University, Portland, OR, USA, in 1986.

Dr. Xu serves as the Founding Chair of the International Federation for Information Processing (IFIP) Technical Committee on Information Systems (TC8) Working Group on Enterprise Information Systems (WG8.9) and the Founding Chair of the IEEE SMC Society Technical Committee on Enterprise Information Systems.



Chengen Wang (M'13–SM'13) received the Ph.D. degree from Nanjing University of Aeronautics and Astronautics, Nanjing, China.

He is currently a Professor at the State Key Laboratory of Synthetical Automation for Process Industries, Northeastern University, Shenyang, China, since 1991. His research interests include product assembly planning and simulation, product design optimization, and finite element methods.